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A Study of Groundwater Contamination Due to Saline Water Disposal in the Morrow County Oil Fields

March, 1969

State of Ohio
Water Resources Center
Ohio State University

A STUDY OF GROUNDWATER CONTAMINATION DUE TO SALINE WATER DISPOSAL IN THE MORROW COUNTY OIL FIELDS

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Research Project Completion Report
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Grateful acknowledgement is given to Mr. Jimmy E. Shaw, who initiated the work on this project and developed the first stage of the work into a valuable Master's thesis. We wish also to express appreciation to Mr. Ted Clark, whose supervision of our field work throughout the project's three years was thorough and creative, and to Michel Robinson, James Carroll, and James Curl, who assisted Mr. Clark during various stages of the work.

INTRODUCTION

Previous work: As a direct result of this project, two technical reports in the form of master's theses have been written. They are as follows:

Shaw, Jimmy E., 1966, An Investigation of Ground-water Contamination by Oil-field Brine Disposal in Morrow and Delaware Counties, Ohio, M. S. Thesis, The Ohio State University, 127 p.

Boster, Ronald S., 1967, A Study of Ground-water Contamination Due to Oil-field Brines in Morrow and Delaware Counties, Ohio, with Emphasis on Detection Utilizing Electrical Resistivity Techniques, M. S. Thesis, The Ohio State University, 193 p.

These two works cover nearly all aspects of the project's endeavors. It would be redundant to repeat all of what Shaw and Boster have written in this report, therefore, this report is presented with the idea of summarizing the two theses in the area of investigative techniques and incorporating the conclusions in the form of a consise statement. With regard to the topics covered in the two theses, they are seen as complete within the work undertaken by the project's staff members. To aid the reader with future reference work, the table of contents from both theses are presented as Table 1 and Table 2.

Copies of the above-mentioned theses are distributed as follows: 2 each to the Ohio State University's Libraries, 1 each to the Water Resources Center of The Ohio State University, and 1 each to the Office of Water Resources Research, U. S. Department of Interior.

In addition to the two theses, a term paper has been included in the report because of the direct relationship to this project. Mr. Ted Clark, Department

AN INVESTIGATION OF GROUND-WATER CONTAMINATION BY OIL-FIELD BRINE DISPOSAL IN MORROW AND DELAWARE COUNTIES, OHIO

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Table 1

A STUDY OF GROUND-WATER CONTAMINATION DUE TO OIL-FIELD BRINES IN MORROW AND DELAWARE COUNTIES, OHIO, WITH EMPHASIS ON DETECTION UTILIZING ELECTRICAL RESISTIVITY TECHNIQUES

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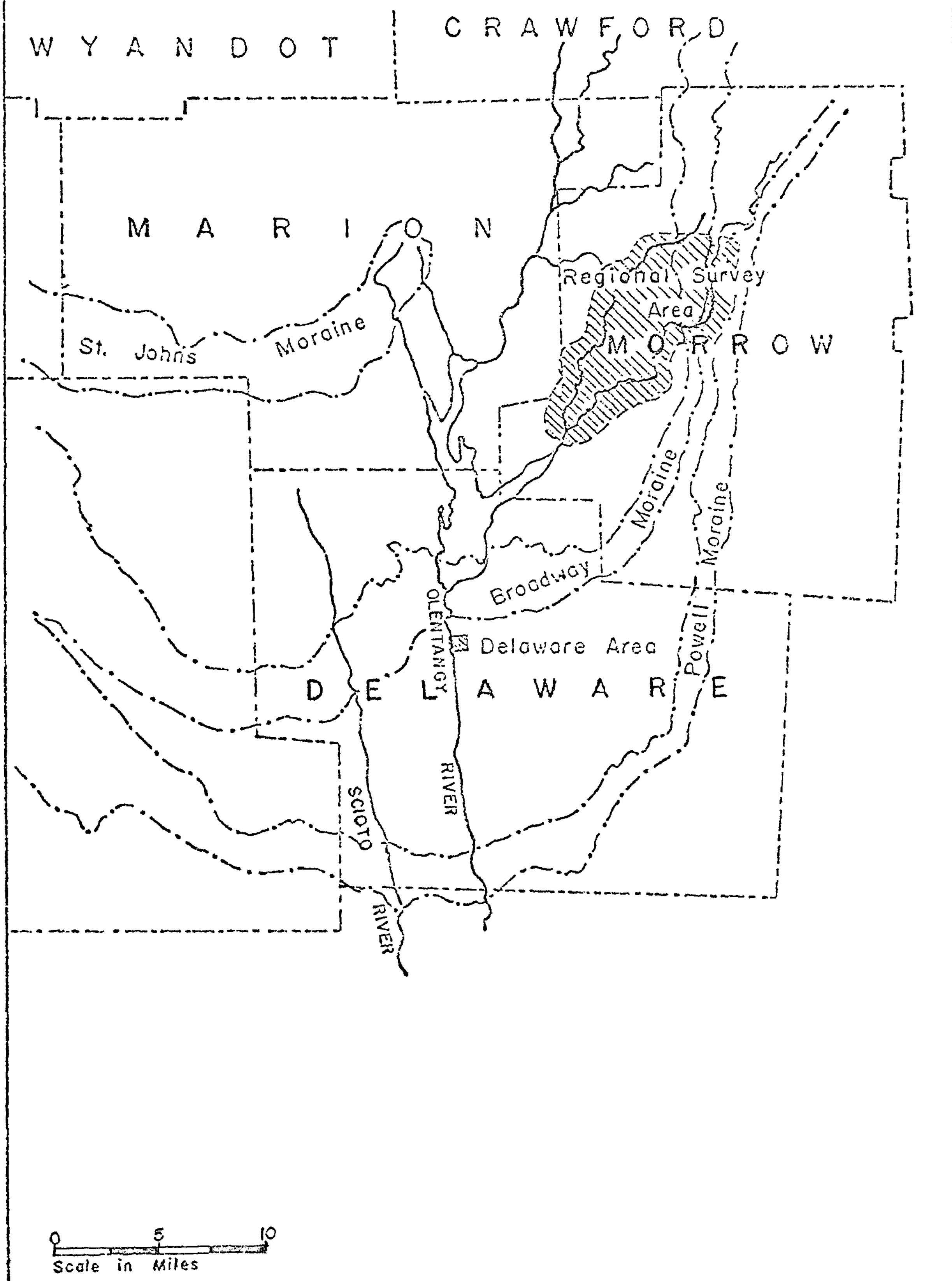
Table 2

of Geology, The Ohio State University, is the author of the paper which deals with the design and construction of a large ground-water model built with project funds.

Scope of the project: The purpose of the project was to study the effects of pollution of the ground water in Morrow and Delaware Counties, Ohio, due to the introduction of saline oil field wastes through evaporation pits. The investigation was directed toward the determination of the source, severity, areal extent, and probable future movement of the pollution. Emphasis was placed upon methods of detection of such contamination.

Background and History: The Morrow County survey area is best described by Shaw as follows:

> "Location And General Features
>
> The Morrow County survey area lies in the northeast portion of the Scioto River drainage basin. The principal tributary in this part of the basin is the Olentangy River (Table 3). The Olentangy River heads in the northeastern corner of the basin, runs through Crawford, Marion, Delaware, and Franklin Counties and empties into the Scioto River at Columbus. The major tributary of the Olentangy River is Whetstone Creek, which drains 114 square miles and is the east boundary of the survey area. Shaw Creek drains 30 square miles and limits the survey area on the west.
>
> The survey area is a till plain with relatively steep slopes along the streams but generally flat elsewhere. Two prominent end moraines lie along each side of Whetstone Creek north of Mt. Gilead, Ohio. The Broadway Moraine to the west of the creek and the Powell Moraine to the east were laid down on preglacial topography that stood higher than the area to the west; consequently topographic relief is greater along Whetstone Creek than over the rest of the area. Elevations range from approximately 1200 feet above sea level in the northeastern part of the area to about



Index map for Regional and Delaware Survey Areas

Table 3

J. E. Shaw, 1966

950 feet in the southwest.

The area surveyed, covering approximately 60 square miles, includes Mt. Gilead with a 1960 population of 2788, Cardington with 1109, and Edison with 386."

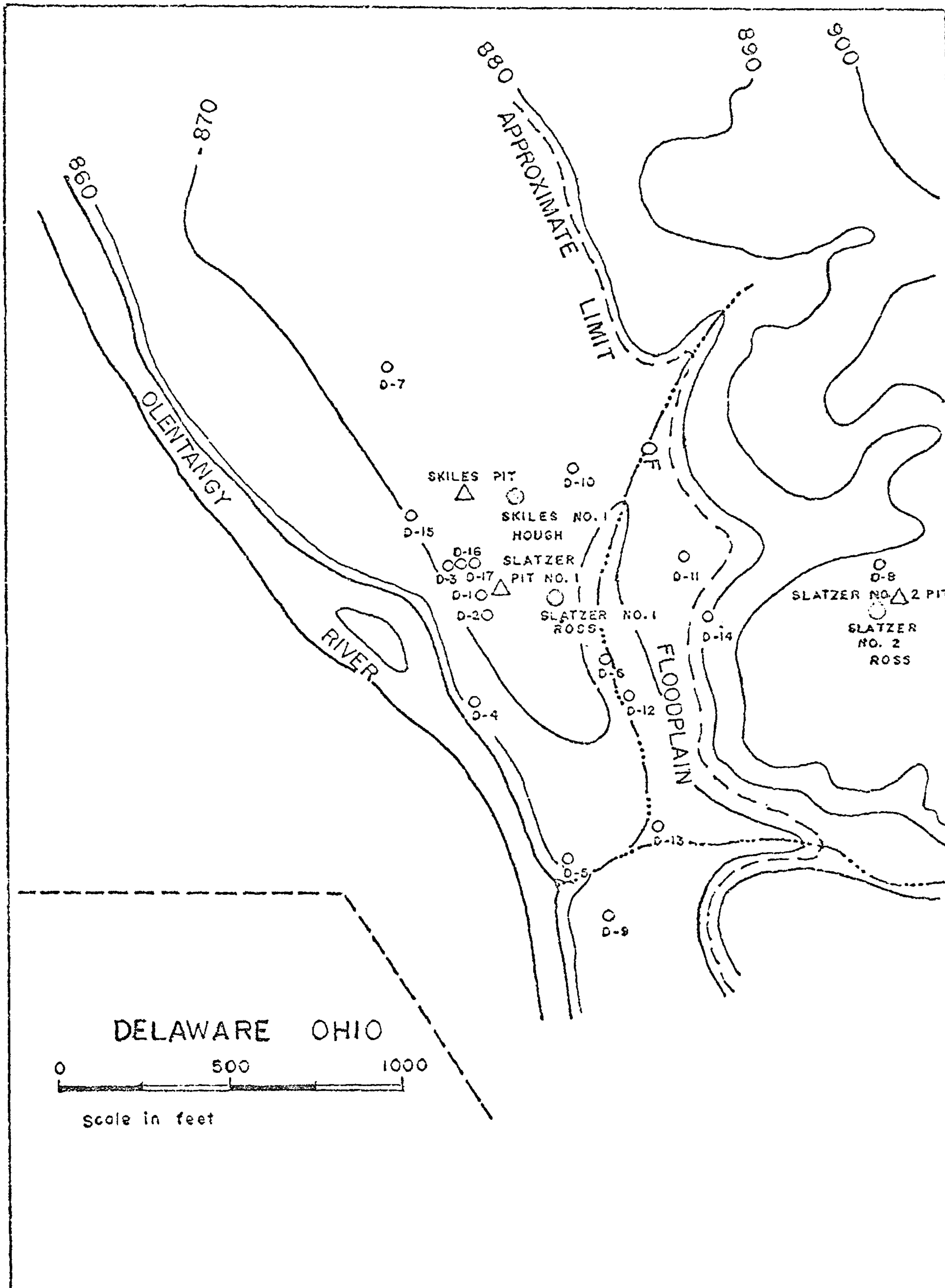
The Delaware survey site is described by Shaw as follows:

"Location and General Features

The Delaware area lies in the floodplain of the Olentangy River, just northeast of the city of Delaware, Ohio (Table 4). The floodplain deposits, composed primarily of coarse sands and gravels with interbedded silts and clays, range in thickness from 10 to 25 feet, and are found in a band approximately one-half mile wide along the river channel. Surface relief across the floodplain is slight, the elevations increasing from 865 feet near the river channel to 880 feet on its east side (Table 5) and (Table 4). To the east, elevations increase about 60 feet to flat table lands above the floodplain. This topographically high area is underlain by red silts and shales with stringers of hard, well indurated shales occurring throughout the section. This material is relatively impermeable, and the shale stringers act as carriers to downward-percolating water, resulting in seeps along road cuts and at numerous locations around the margins of the slopes where the shale stringers crop out.

Ground water is plentiful in the floodplain deposits, and where gravel lenses are found, an excellent near-surface fresh water source occurs. The water table is very near the surface; maximum depth to water in January, 1966, was six feet at D-15 and minimum depth was one and one-half feet at D-12. The water table gradient (Table 6) is steep, sloping from 869 feet at D-1 and D-2 to 859 feet at D-5, approximately 1: 80. Since ground water velocity is directly proportional to the water table gradient, ground water exchange through the reservoir is rapid."

In both areas, unconsolidated clays, sands, and gravels are underlain by impermeable bedrock. In Morrow County, this bedrock is the Ohio Black Shale (Devonian) and in the Delaware area it is the Delaware Limestone (Devonian). No outcrops of bedrock are known to occur in either area, but the bedrock is exposed in streams below the waterline in both counties. Shaw has also described the



Delaware area map showing observation wells, oil wells and disposal pits. Contouring shows surface relief across floodplain.

Table 4

J.E. Shaw, 1966

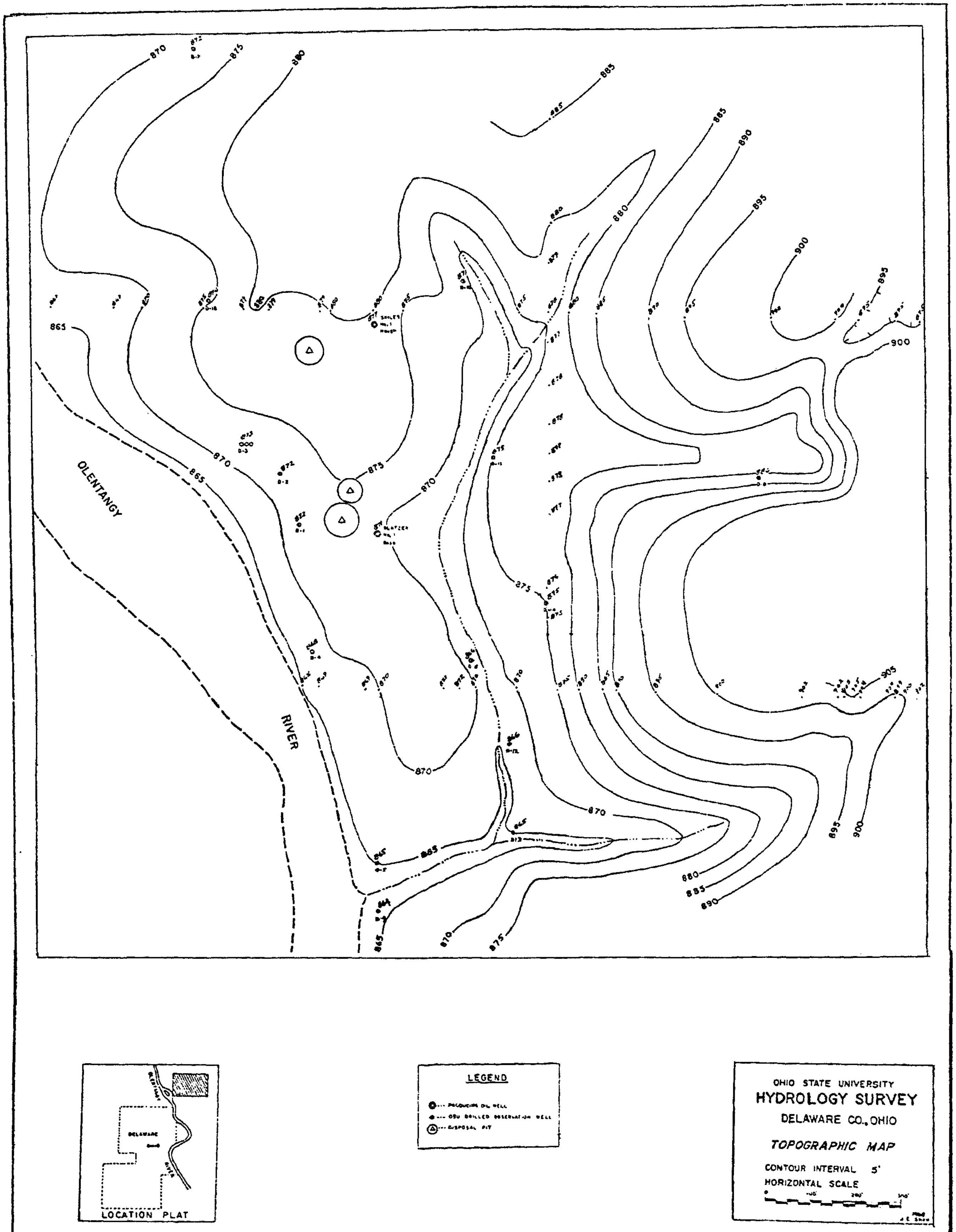

OLENTANGY
RIVER
LEGEND
PRODUCING OIL WELL
OSU DRILLED OBSERVATION WELL
DISPOSAL PIT
OHIO STATE UNIVERSITY
HYDROLOGY SURVEY
DELAWARE CO., OHIO
TOPOGRAPHIC MAP
CONTOUR INTERVAL 5'
HORIZONTAL SCALE
LOCATION PLAT
DELAWARE

Table 5

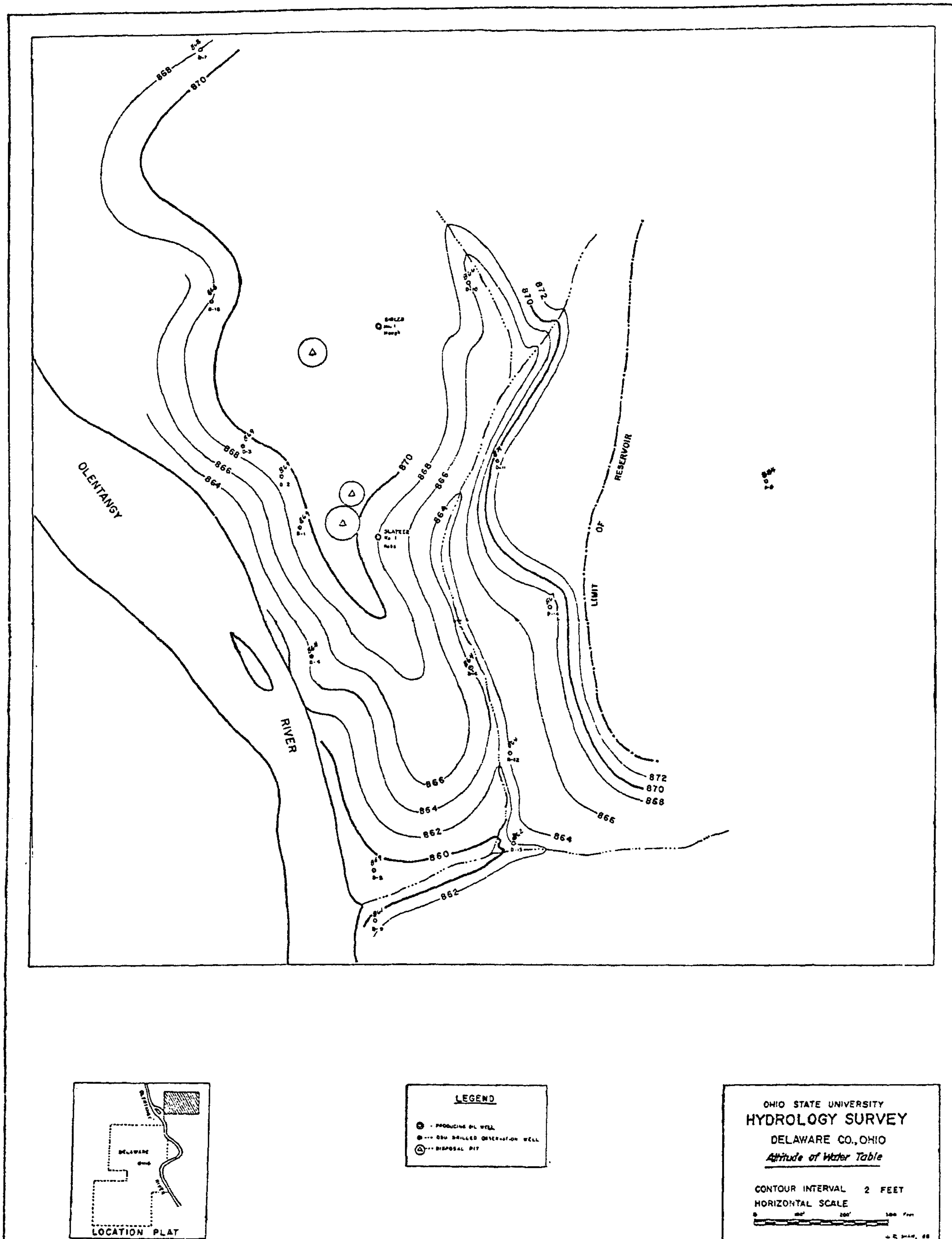

OLENTANGY
RIVER
LIMIT OF RESERVOIR
868
870
872
866
864
862
860
LOCATION PLAT
LEGEND
PRODUCING OIL WELL
OSU DRILLED OBSERVATION WELL
DISPOSAL PIT
OHIO STATE UNIVERSITY
HYDROLOGY SURVEY
DELAWARE CO., OHIO
Altitude of Water Table
CONTOUR INTERVAL 2 FEET
HORIZONTAL SCALE

Table 6

glacial history of the Morrow County survey area (p. 11).

In 1961 a flowing well was completed in Morrow County. This well touched off what truly can be termed an "oil boom". More than 2000 oil wells were drilled within three years, with more than 600 becoming producers. The oil is trapped in buried erosional hills of the Copper Ridge Dolomite (Cambrian) by overlying unconformal Ordovician shales. The depth of the wells usually run between 3000 and 3500 feet.

As with any oil recovery operation, brine is produced as a byproduct of the crude oil. In most cases, this highly mineralized water must be disposed of and the cheaper the disposal method, the more desirable it becomes. This philosophy has led to numerous instances of ground and surface water pollution in this county and elsewhere. In the absence of enforceable laws there is little but common sense to restrict an oil producer from disposing of brines in any imaginable manner.

This is exactly the situation that occurred in Morrow and Delaware Counties following the discovery and during the development of the oil fields. More than 25 million barrels of crude oil were extracted from the Morrow County oil pools and it has been estimated by Shaw that nearly that much brine was also produced and subsequently disposed of in the county. This brings one to a consideration of the various methods employed for disposal of this waste. Analysis of these methods provides the necessary information to understand how groundwater aquifers may be polluted by oil recovery-related operations.

Table 7 is a schematic drawing that shows the various disposal methods.

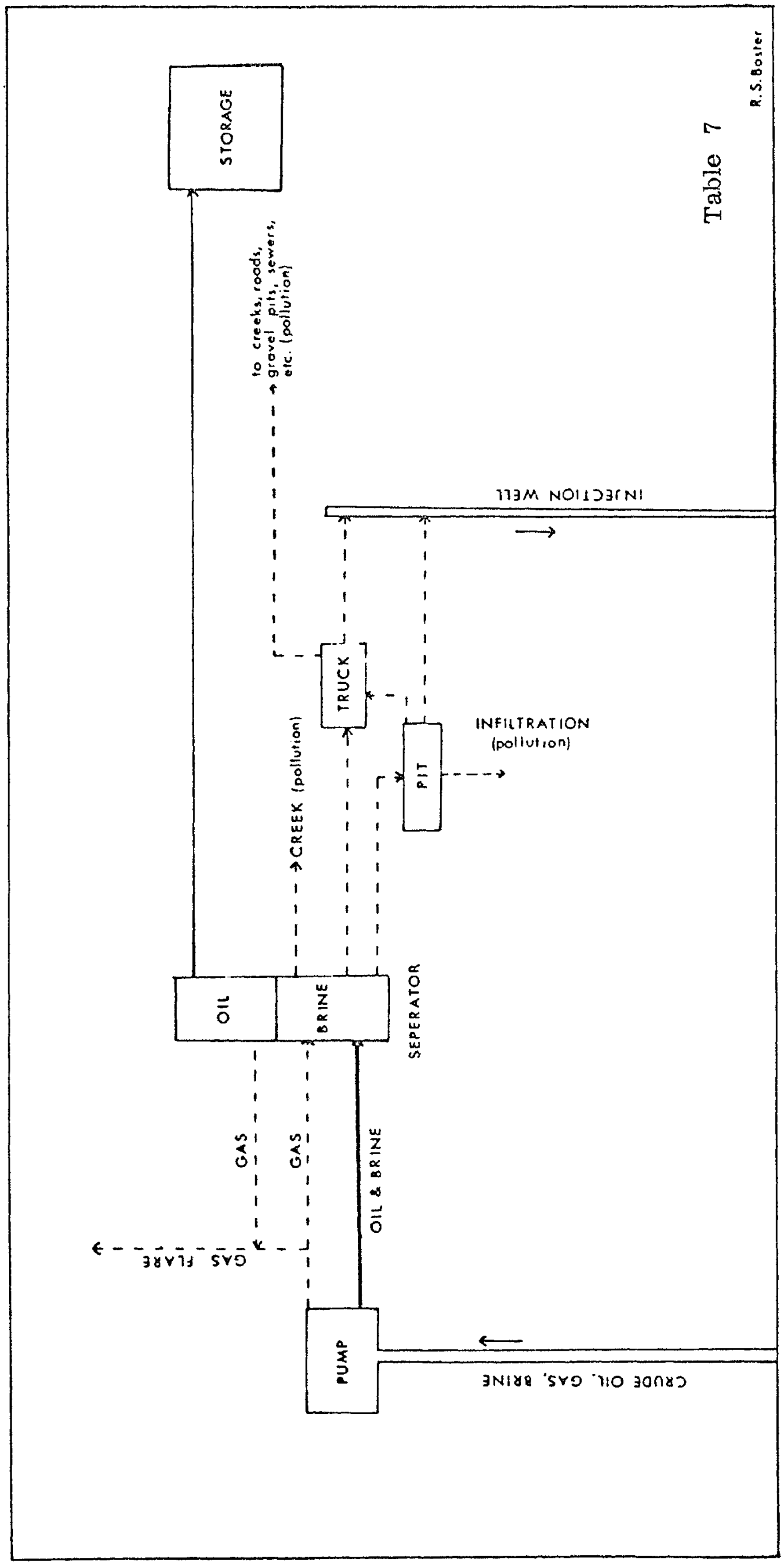

STORAGE
to creeks, roads, gravel pits, sewers, etc. (pollution)
INJECTION WELL
TRUCK
INFILTRATION (pollution)
PIT
CREEK (pollution)
OIL
BRINE
SEPERATOR
GAS
GAS
OIL & BRINE
GAS FLARE
PUMP
CRUDE OIL, GAS, BRINE
R.S.Boster

Table 7

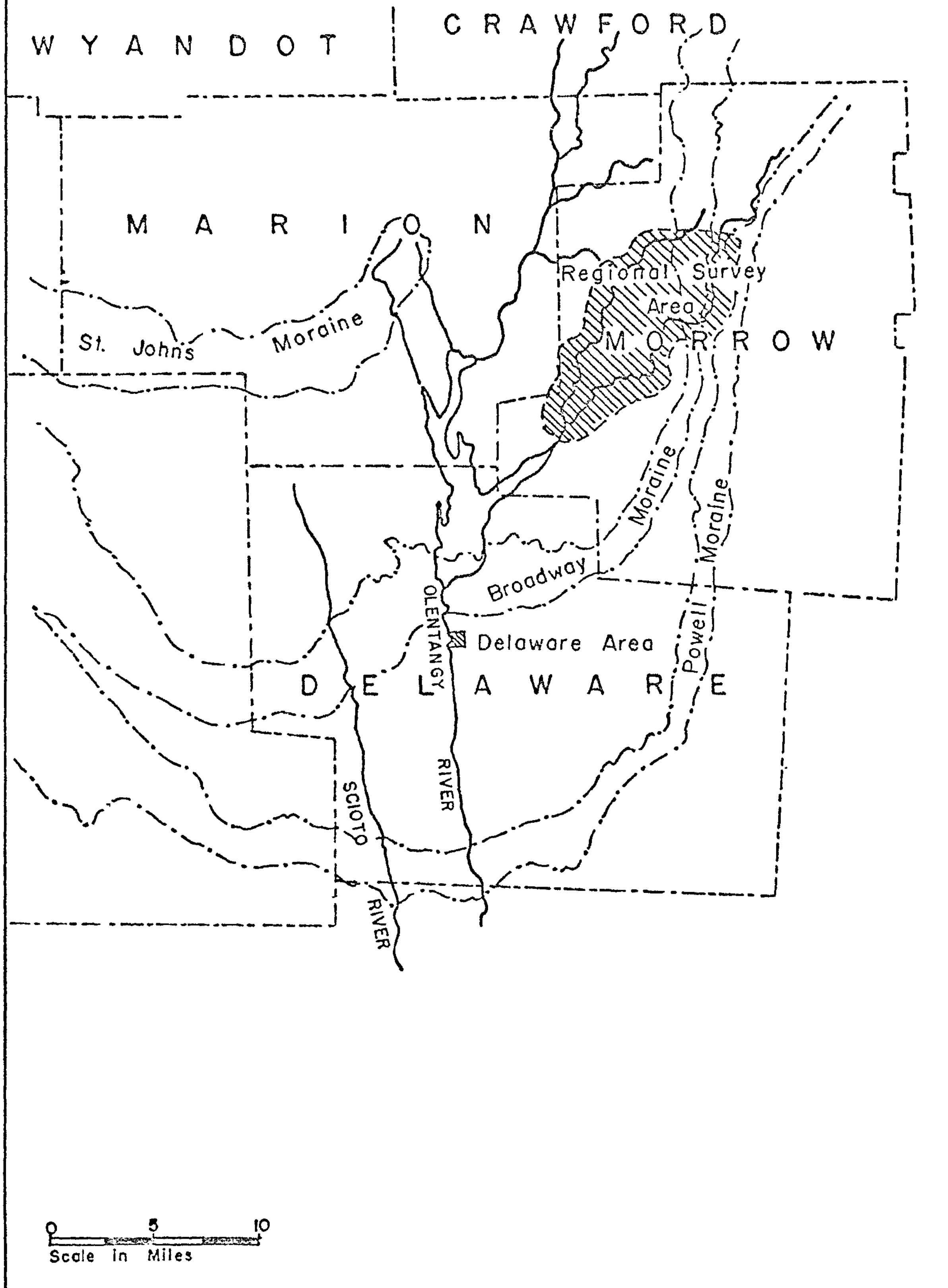
Once the brine has left the separator, there are several paths it may take--some leading to pollution of water supplies or waterways, and some which can be considered effective disposal methods. At present, under new laws and regulations enforced by the Ohio Division of Oil and Gas, the only legal method of disposal is by means of an injection well. Such wells are used to move the brine from the surface or near-surface to a low geologic horizon where no interaction with potable water supplies is to be anticipated. In fact, such methods are widely used in the petroleum industry as a means of secondary recovery. Barring leakage in the well's casing this is the safest and most effective method of brine disposal. It is also the most expensive. However, the use of pre-existing dry oil wells greatly cuts the costs of such a disposal system.

Another method whose effectiveness is a subject of some debate is the so-called "evaporation" pit. An evaporation pit is a buldozed hole in the ground. Their size will vary, but in the Morrow County and Delaware County areas the typical size would be about 20 by 25 feet and about 5-7 feet deep. It is claimed by proponents of this disposal method that considerable volume reduction can be achieved by evaporation to the atmosphere. However, evaporation is only effective where climatic conditions are favorable, and such conditions do not exist in Ohio. In Texas, for example, where the evaporation rate may be several feet per year, evaporation pits may be effective in reducing the volume of oil-field waters, but the concentrated saline waste is still left behind. In Ohio, where the evaporation rate is low because of the humid climate, evaporation rates are too low even to effectively reduce water volume. Instead of evaporating their contents, "evaporation" pits in Morrow and Delaware Counties seeped their contents into the underlying ground, and the highly mineralized contents eventually reach the water table and an aquifer becomes contaminated. This type of contamination can be avoided by lining the pits with a clay such as bentonite or a plastic tarp. A further problem complicating pit operation is the fact that an oil film or scum usually forms on the surface of the brine in the pit and this film greatly retards evaporation. It is then necessary to "burn off" or skim these pits to ensure as rapid evaporation as possible. Both Boster and Shaw concluded that unlined "evaporation" pits were the major cause of the ground water contamination in the two research areas.

Other means of contamination include hauling by tank truck with subsequent spreading or dumping on roads, in streams, or in gravel quarries. Widespread evidence of these types of disposal was noted during the survey. But in total, it is considered minor with respect to the pits.

As an aid to the reader of this report, Table 8 is included to show the shaded location of the two survey areas. Table 9 is an isochlor map of the Morrow County as prepared by Shaw. Table 10 is an isochlor map of the Delaware enclave.

The ground-water contamination in Morrow County came to light in 1964, which was already too late to protect the aquifers. At this time the village of Cardington, located in the center of the oil boom, was forced to abandon their municipal well because of an influx of contaminants that must have originated from an "evaporation" pit within 150 feet of the well. At about the same time,



Index map for Regional and Delaware Survey Areas

Table 8

J.E. Shaw, 1966

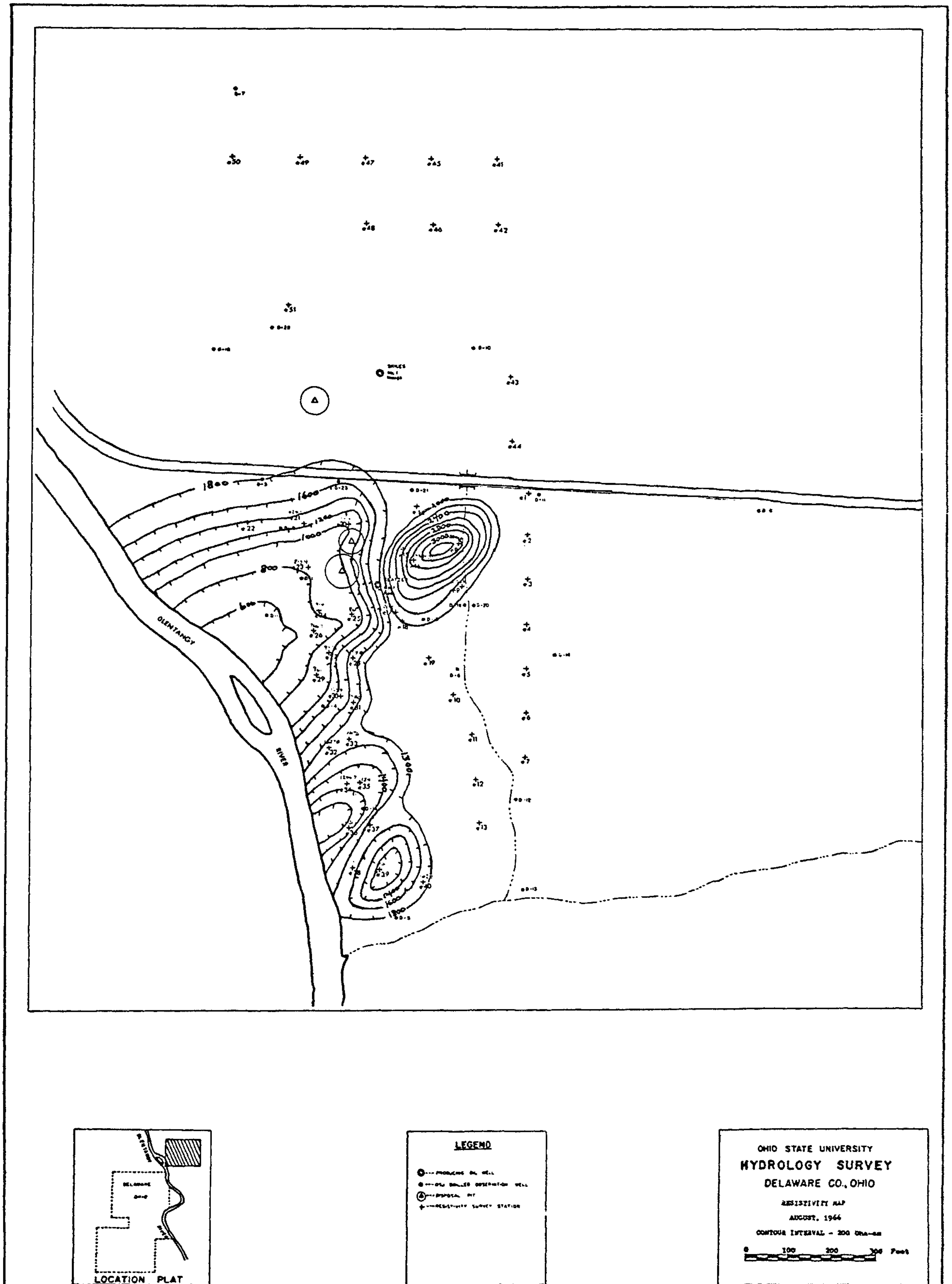

1800
1600
1000
800
600
OLENTANGY
RIVER
LOCATION PLAT
LEGEND
OHIO STATE UNIVERSITY
HYDROLOGY SURVEY
DELAWARE CO., OHIO
AUGUST, 1966
0 100 200 300 Feet

Table 9

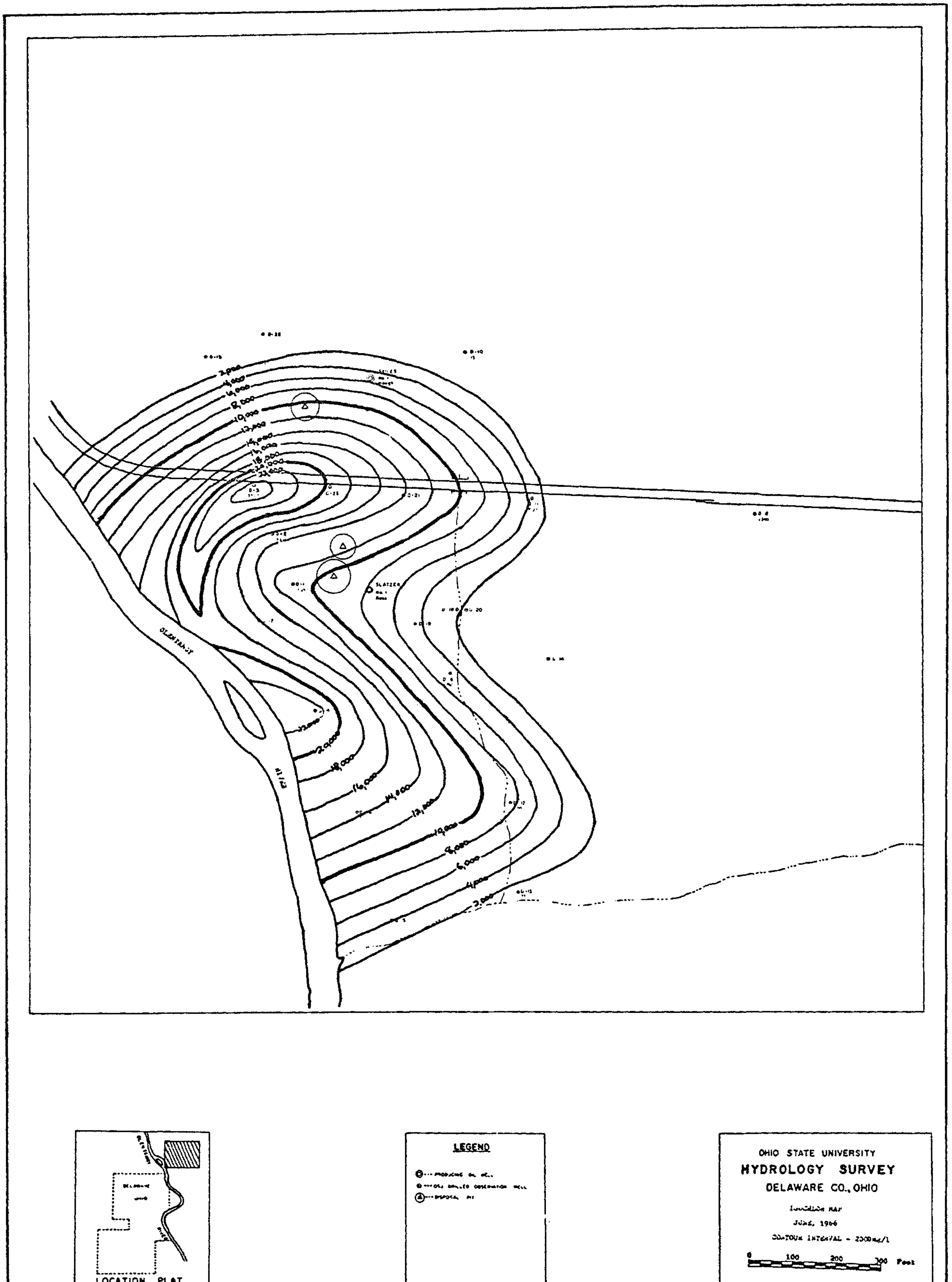

2,000
4,000
6,000
8,000
10,000
12,000
14,000
16,000
18,000
20,000
22,000
SLATZER
OLENTANGY
LOCATION PLAT
LEGEND
OHIO STATE UNIVERSITY
HYDROLOGY SURVEY
DELAWARE CO., OHIO
0
100
200
300
Feet

Table 10

the Ohio Division of Health initiated a surveillance program of the streams upstream and downstream from the major Morrow County producing area.

The results of the surveillance program are discussed by Shaw. High chloride concentrations in the streams were attributed to dumping by contract truckers (an enterprise which at one time was a thriving business in Morrow County). A significant proportion was also contributed by ground-water that is effluent to the streams. This is based upon an inverse relationship with discharge and evident from the data of the surveillance program.

The contamination causing the Delaware enclave is the result of operation of two disposal pits. One pit was in operation for 13 months and the other in operation for 15 months. Shaw calculated that more than 225,000 barrels of brine were emptied into these pits and subsequently infiltrated into the ground water aquifer.

Ground-water characteristics (Morrow County): The Morrow County research area is underlain by Pleistocene till of variable composition. Boster has described the ground-water characteristics as follows:

> "The composition of the till is quite variable. Evidence of this comes from many existing water-well logs and from wells drilled expressly for this study. The topsoil is generally a clay loam. A typical well log follows.

Depth (ft)	Description
0-5	Overburden (clay loam)
5-9	Gray-brown silt loam, some sand strings
9-15	Yellow-brown caly-rich loam, gravel strings
15-21	Blue-gray clay loam with sand strings

Depth (ft)	Description
21-26	Gray to gray-black sandy loam, clay lenses present

(water table at 12 feet)

Domestic water supply in the area is obtained from drilled or dug wells and from spring water. The well capacities range from a "seepage" well capable of producing less than a few gallons per minute to wells whose maximum capacity is in excess of several hundred G. P. M. Poorer wells result most commonly from the casing and well point being set in clay which has a very low permeability. Drillers in the area usually refer to this clay as "bedrock". This leads to confusion when interpreting well logs. Higher capacity wells are set in unconsolidated sand of high permeability. Because of the highly variable nature of the till, ground-water velocities will vary throughout the area. Movement of contaminated ground water, therefore, varies within the survey area. In addition, chemical processes, particularly ion-exchange activity, will vary because of differing chemical composition of the till.

Underlying the till is the Ohio Shale (Devonian). Usually referred to as "slate" by local drillers, the shale is a thick, dense, black material, and quite impervious to ground water except where jointing is well developed. Many deep water wells are drilled into the shale where the till is a poor producer or where the driller is a good salesman. These wells have little chance of encountering a good water supply within the shale, but the increasing borehole volume with depth and minor seepage through the exposed shale face will usually produce sufficient water for domestic use. The shale contains variable amounts of pyrite (FeS_2) which causes some wells in the area to produce highly sulfinated water. Sulfur-rich water may also be encountered in wells not set into the shale and can be attributed to chemical weathering.

The significance of the relatively impermeable shale in terms of ground-water hydrology is that it acts as an effective hydraulic seal beneath the ground water in the till. Therefore, any pollutants dissolved in the ground water will normally be confined to the till with minimum migration below the till-shale interface.

The quality of ground water in this area is extremely variable. Nevertheless, certain general statements concerning water quality can be made. As with most ground waters, hardness is high, usually about 400 mg/l as $CaCO_3$. Chloride concentration in uncontaminated areas is low, normally less than 10 mg/l. The U. S. Public Health Service has established for some time an upper limit of 250 mg/l for chloride-ion concentration (1946). A person with very sensitive taste buds can barely detect such a concentration. The low natural chloride concentration is the prime factor in detecting brine contamination, since chloride is the dominant anion in brine (Levorsen, 1967, p. 166; Shaw, 1966, p. 2).

Precipitation in the Morrow County area approximates 37 inches per year with an average yearly temperature of 52 degrees Farenheit (Water Inventory of Scioto River Basin, 1963). Ground water in the area is sufficient to support two minor effluent streams throughout the year. The ground water originates as meteoric water which infiltrates the ground surface and moves down to the water table. Seasonal variation in water-table attitude have been discussed by Shaw (1966) and by Robinson (1967)."

The Delaware area is described by Boster as follows:

"The floodplain is underlain by coarse sands and gravels with interbedded clay and silt layers. Bedrock is consistantly present at depths of from 20 to 25 feet based upon resistivity surveys by this investigator. The bedrock is a dense, impervious limestone, the Delaware Limestone (Devonian), which does not outcrop in the area but is exposed below the water line in the adjacent Olentangy River. Because of buried boulders and the limited capacity of drilling equipment, the depth to bedrock could not be determined with certainty by drilling.

The water table in the area is high and commonly less than three feet from the surface. Water wells drilled in the floodplain deposits are capable of producing high yields because of the highly permeable nature of the materials. Owing to the high permeability and existence of a steep water-table gradient, Shaw calculated the ground-water flow velocity to be greater than 1.5 feet per day (1966, p. 90)....Tight hydrologic control exists in the area. Bounding the area on the west is the Olentangy River which is a ground-water divide. Water table surveys indicate that most of the ground water is moving toward the Olentangy River. However, some mounding of ground water occurred while the pits were in operation. This is evident from the high chloride concentrations in observation wells east of the pits. It seems probable that a considerable amount of contamination in this area east of the pits could be due to "ionic mounding" caused by chloride-concentration gradients. Because the water table is close to the surface and, in fact, intersects the water table in the pits (when not in use), this type of mounding may be the major factor causing high chloride concentrations upgradient from the pits.

The enclave is bounded on the south by a small tributary, Saunders Creek, which is an intermittent stream and therefore would be expected to be a partial ground-water divide. Likewise, the north-south trending waterway which bounds the area on the east is probably also a partial ground-water divide. This man-made cut has recently been tiled and covered with soil north of the road passing through the area. This accounts for omission of the cut on several plates in this thesis.

Although there is no natural or man-made boundary to the north of the enclave, access to this area and detection methods enable its definition.

As previously mentioned, the floodplain is underlain by an impervious limestone to a depth of slightly more than 20 feet. This provides an effective hydraulic seal. The entire enclave is seen as being very well-defined since all boundaries are known or determinable."

Chloride stratification with depth: Shaw observed that as the brine infiltrated from the Ross pit (Delaware, Ohio) began to move laterally down the water-table gradient, there was an inversion from "high chloride concentration near the top of the reservoir to high concentrations near the bottom. Shaw has proposed a mechanism for the observed phenomenon (p. 87), saying that it is due to a combination of mounding around the pit, the water-table slope, the depth to the bedrock, input of the pit, and physical character of the aquifer. The major factors causing the inversion phenomenon must be attributed to the higher density of the highly mineralized contaminates and the dynamic condition of the natural ground water. Special wells within close proximity of each other and completed in such a manner to only permit water entrance at a specified depth were used in studies of this type.

Shaw found exactly the same situation in the Morrow County survey area.

He explained it in the following way:

> "Although the contaminated water has a greater denisty than uncontaminated water and would eventually settle to the bottom of the reservoir, the greater rate of water movement at the upper boundary of the water table sweeps the contaminated water along, preventing it from mixing completely with the water below. Where ground-water movement is rapid and the distance to the point of discharge into a surface stream is small, the higher chloride water will be found at shallow levels. But where the time of residence of the ground water within the reservoir increases, inversion should occur and the lower levels of the ground-water body would then show the higher chloride. (p. 68).

Shaw's evaluation of the inversion of the salt concentration with time, lead to the conclusion that, "In areas where the upper levels of the reservoir are contaminated, it is almost certain that high chloride water is being introduced from the surface" (p. 69).

<u>The enclave concept:</u> Throughout the duration of the project it was necessary to refer to areas of ground-water contamination. The term "enclave" seemed to serve this purpose. An enclave is defined here as a volume of contaminated ground-water. Enclaves can be represented in isochlor maps, resistivity maps, and conductivity maps, but such maps only indicate the areal extent of the enclave. It must be borne in mind that an enclave is actually a <u>volume</u> of ground water whose quality has been altered by the influx of contaminates of one kind or another, in this case--brines.

<u>Method of Investigation:</u> To study the contamination problem in both areas several methods were employed. These include isochlor, conductivity, and resistivity mapping, mathematical analysis of chloride samples, and chloride and

conductivity surveys in the waterways traversing the survey area. All of these are covered in detail in either Shaw's or Boster's theses and will only be summarized in this report.

In Morrow County more than 300 domestic wells were selected for monitoring. Residents were supplied with collection bottles and asked to deposit a filled bottle at the proper time at one of three collection stations set up by the project in Mt. Gilead, Cardington, and Edison, Ohio. Reminders were sent via postal cards prior to the desired collection date. Those residents who did not make the deposits had their samples collected by route work conducted by project workers following an inventory of the collection center deposits.

In addition to the several hundred domestic wells, the project drilled 30 wells in Morrow County to better define the characteristics of the contamination. These wells were drilled with an auger-type jeep-mounted rig and were developed in conventional ways using a gravel pack in the anular space. In addition to these wells, 6 larger diameter wells were drilled and mounted with Stevens automatic recorders. The purpose of these wells was to study the fluctuations of the water-table attitude throughout the duration of the project. Samples were not taken from these wells since they were usually very close to a sampled well and since sampling might interfere with the recording mechanism on the wells.

Samples collected in the above-mentioned manner were analyzed for chloride, and sometimes for conductivity, at the Water Resources Center of The Ohio State University.

Resistivity studies were conducted by Boster and they comprise the major portion of his thesis. Two Soiltest resistivity instruments were employed, the Model R-30 "Michimho", and the Model R-40 "Strata-scout". Resistivity studies have long been employed by engineers and ground-water hydrologists for determination of bedrock and water-table attitudes. Because electrical resistivity is dependent upon the electrical properties of the subsurface fluids, it was used as a means of detecting electrolytic ground-water contamination in both survey areas with good success. This aspect of the project is presented in more detail in a subsequent chapter of this report. For a very detailed description of this type of investigation the reader is directed to Chapter 7 of Boster's thesis.

To test the ability to detect stream pollution due to effluent contaminated ground water, stream surveys were initiated in the summer of 1966. These consisted of detailed chloride and conductivity analyses in many reaches of the three principal streams in the research areas; Whetstone and Shaw Creeks, and the Olentangy River. These surveys will be reviewed in this report. For a more detailed discussion, the reader is directed to Chapter 8 of Boster's thesis.

CHLORIDE STUDIES

The composition of a brine from an oil-recovery operation will vary from pool to pool and often within the same pool. During the course of the project, several brine samples were analyzed. It was not surprising to find that the chloride ion was easily the dominate anion dissolved in the oil-field waters. Often, the chloride concentrations were in excess of one-half the total dissolved solids. Chloride concentrations varied from 35,000 mg/l in the Delaware area to over 100,000 mg/l in the Morrow County research area. It was known that the average chloride concentration for fresh ground waters in both areas was less than 10 mg/l. Therefore, the use of chloride-concentration data is seen as an easy means of detecting ground-water contamination in this study.

Samples taken from wells were analyzed for chloride at the Water Resources Center of The Ohio State University. The Mohr quantitative titration method employing silver nitrate was employed throughout the projects (Standard Methods, 1960). Although a more accurate method, the Mercurimetric method, has recently been accepted by "Standard Methods" the Mohr method was found to provide excellent results that were well within the desired range of accuracy.

As mentioned previously, some wells were drilled especially for the project. Sampling of these wells was accomplished by one of three methods: a hand operated "pitcher" pump, a gas-engine pump (also used to develop the wells), and a "thief" pipe designed by Mr. Ted Clark, research assistant for the project. Because of the possibility that water may be retained in the well-pipe's bore space, these wells were pumped for a time prior to taking the sample. Following conventional collection procedures, bottles were rinsed with collection water prior to filling.

Samples were collected on a bi-monthly schedule in Morrow County, and on a monthly schedule in Delaware County. From the chemical analysis, isochlor maps were made by plotting the titration values on base maps prepared for that purpose. The annual reports for the project contain reprints of several isochlor maps from both survey areas. In addition, a significant portion of Shaw's and Boster's theses are concerned with this type of map. Isochlor maps were not prepared for the second year of study in the Morrow County research area, however, the chloride data was used extensively for the study of enclave movement and behavior.

Of the three major means of mapping undertaken by Boster, isochlor mapping was considered the most reliable. For this reason, conductivity and resistivity maps were compared to configurations of isochlor (for the same month) in order to evaluate their accuracy in depicting the characteristics of an enclave.

Considerably discretion must be exercised when interpreting isochlor maps. From a study of the monthly fluctuations of the chloride concentrations of observation wells in the Delaware enclave, it became apparent that little faith could be placed upon a given well value. To quote from Boster:

> If all the wells were to have their concentrations doubled and a map prepared, the resulting enclave would be identical to a map of the original well values. The size of the enclave would remain nearly constant and the configuration would be identical. In other words, changes in chloride concentrations do not necessarily change the

> physical characteristics (size and configuration) of the enclave. Only when wells change independently of each other will these characteristics be altered. Isochlor maps are best studied with reference to only these two characteristics. It is not recommended that they be studied for chemical changes in view of the erratic nature of the data in (Table 11). For example, following one particular isochlor line from month to month may lead to erroneous interpretations. (p. 39).

The above-quoted conclusion is based upon analysis of many isochlor maps. The point to be made is that isochlor mapping can be a very helpful diagnostic tool, but that quantitative interpretations must be made with caution.

Ground-water studies can benefit from chloride analysis by other ways than mapping. For example, an estimate of the amount of effluent ground water to an effluent stream was made by Boster for the reach of the Olentangy River adjacent to the Delaware enclave. This is discussed in a subsequent section of this report and in Chapter 3 of his thesis. Shaw derived two methods using chloride data whereby the time at which the enclave would be considered cleared could be estimated. Chloride studies also helped detect stream pollution in many river surveys. Ground-water velocities were calculated by Shaw using chloride data. Therefore, the use of chloride data is very significant in this type of ground-water study. It has been shown by this investigation that chloride data provide the most reliable information for interpretation of this type of ground-water pollution.

<u>Enclave dissipation with time:</u> In order to estimate the time required for an enclave to clear it is desirable to know the amount of salt introduced to the ground-water aquifer, and the velocity of enclave movement. Dispersion of mixing rates are also desirable parameters. In Morrow County, the quantities of brine intro-

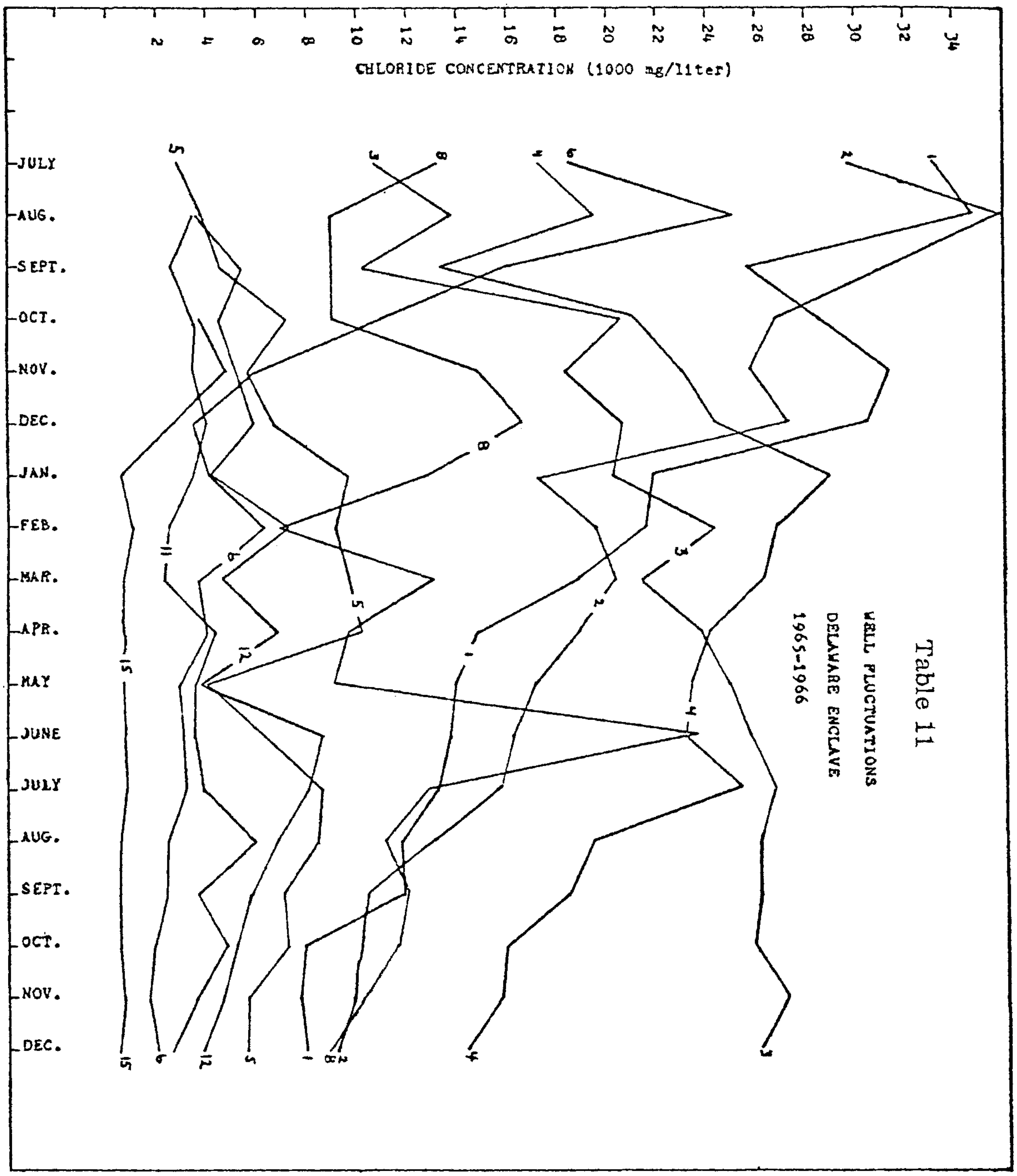


Table 11
WELL FLUCTUATIONS
DELAWARE ENCLAVE
1965-1966

duced into the ground-water aquifers could not be determined since Ohio law did not require the reporting of the quantities of brine produced in the oil-fields. Further difficulties include the fact that velocities of ground water in various Morrow County aquifers vary considerably even within a single aquifer. Because of these difficulties, it was impossible to make precise predictions concerning how much time would be required to clear the aquifers in Morrow County. However, it is apparent from isochlor maps (by Shaw) that the contamination will be detectable in the area for many years to come. The time of return to normalcy must be reckoned in terms of tens of years.

Because of the excellent hydrologic and geological control that existed in the Delaware research area, predictions concerning the length of time required to flush the aquifer could be made. Shaw presented two methods based upon chloride data that can be used to make such a prediction:

> The first involves the use of adjacent isochlor maps. By determining the area and average chlorinity between adjacent isochlors and estimating the saturated thickness and porosity of the aquifer, it was possible to estimate the tonage of chloride in the enclave for a given month. Subsequent calculations for other months permit extrapolation to the extinction date of the excess chloride. (Boster, p. 41).

Using Shaw's data, Boster calculated the extinction date to be December, 1972 (p. 43). This was calculated by changing the slope of the depletion curve employed by Shaw and adjusting the estimate for the saturated thickness of the aquifer. The reason that the enclave may be expected to clear by natural processes in so short a time (compared to Morrow County enclaves) is due to the hydrologic conditions present in Delaware. For example, the enclave is in a floodplain with highly permeable sediments that allow rapid transfer of ground water across the floodplain to the adjacent river. In addition the enclave is enclosed by at least two partial ground-water divides, Saunder's Creek on the south, and a man-made drainage canal on the east.

Using the above-mentioned method depletion rates ranged from 13.5 to 32 tons of chloride per month.

Shaw's second method was to compute the time necessary for fresh water from the east to flow through the enclave and discharge into the river. The date calculated was October, 1967, a date now known to be considerably shy of the real extinction date. Boster attributes this discrepancy to ion-exchange activity. The conclusion to be made is that by knowing the ground-water velocity it is not necessarily possible to calculate a clearing date for such an enclave. The problems resolve to the question of what shape the depletion curve must be. It probably is not linear, and it seems likely that it is a curve whose slope decreases with time.

SEVERITY OF CONTAMINATION

One of the problems to which this project was directed was to determine the severity of the ground-water contamination. For many years, the U. S. Public Health Service has established an upper limit of 250 mg/l for chlorides in potable waters. It became apparent early in the project's beginning that several domestic wells used for potable waters had exceeded this amount. It should be noted that a value greater than 250 mg/l is not really a public health concern, in fact, one can hardly taste a concentration of 300 mg/l.

Table A-2 of Boster's thesis shows only six wells (tapped for potable water supplies) with two year chloride concentration averages greater than 250 mg/l. In Delaware, only two domestic wells were monitored. One exceeds the limit of 250 mg/l. It must be noted that some wells in the Morrow County area were closed because of high salt concentrations before samples could be obtained by project staff members. Such an instance represents some economic loss, usually on the part of the well owner. Only two cases are known where a well had to be abandoned by a farmer and a deeper well drilled. It is known that one of these new wells was financed by the oil producer responsible for the pollution of the farmer's well. One of the initial instances which gave this project its start, was the contamination of the village of Cardington's water well, resulting in its abandonment.

When it is recalled that over 400 wells were, at one time or another, monitored and analyzed for chlorides, it must be concluded that the contamination has been minor with respect to U. S. Public Health Standards for chloride. In addition, when the economic loss is weighted against the many millions of dollars exchanged in Morrow County as a result of the oil-recovery and oil-exploitation activities, it is seen to be insignificant. It is unfortunate that some persons had to be adversely affected by having their potable water supply contaminated. Nevertheless, the economic benefits derived by so many of the residents in the county as a result of the oil boom greatly offsets these few unfortunate situations.

AREAL EXTENT OF CONTAMINATION

MORROW COUNTY

Chapter 4 of Boster's thesis is entitled "Areal Extent of Pollution (Morrow County)." A complete discussion of this topic is therein included. The procedure employed and the results will be summarized here. The isochlor maps made by Shaw for his thesis provided a necessary base from which to determine the areal extent of the brine contamination to the ground-water aquifer in Morrow County. Since the normal ground-water concentration of chlorides is less than 10 mg/l, and since 25 mg/l chloride was the lowest isochlor used to draft the maps, the areal extent defined by the total closure created by the 25 mg/l provided a means of estimating the areal extent of the contamination in the regional study area.

Planimetry of the enclaves on Shaw's isochlor maps yielded values which could be transferred to square mile values and the total area affected could be determined. Analysis indicated that the areal extent of the pollution is approximately 13 square miles. In other words, based on the above-mentioned method, 13 square miles of area in the Morrow County survey area is underlain by groundwaters whose concentration is greater than 25 mg/l, a value considered definite evidence of contamination from oil-recovery operations.

An estimate was made of the possible maximum area of pollution in the regional survey area, and this value is 68 square miles. When compared to the value above--13 square miles is approximately 19 per cent of the total possible area of contamination. In other words, nearly one-fifth of the survey area was contaminated with highly mineralized brines.

The above figures were calculated from 6 isochlor maps. Several other conclusions may be made concerning monthly data with regard to enclave movement, dispersion, stability, etc. Such discussion may be found in later chapters of this report.

DELAWARE COUNTY

The areal extent of the Delaware enclave has not changed since the initial isochlor map was made by Shaw in September, 1965. The severity of the pollution has decreased considerably, however, and this is discussed elsewhere in this report.

ENCLAVE MOVEMENT

Isochlor maps are an effective means of detecting and mapping enclaves of ground-water contamination. However, such maps are poor devices for indicating movement of enclaves for several reasons. In the first place, isochlor contours are valuable only in their configuration since their values change with meteoric conditions. Secondly, because of salt-concentration stratification with depth, the developmental history of a sampling well must be considered. In other words, samples from different depths in the saturated zone will often indicate different chloride concentrations. Also to be considered is the known fact that the configuration may change considerably with the absence or addition of sampling wells. This can lead to erroneous conclusions concerning enclave migration and dissipation.

To obtain information concerning enclave movement, a mathematical approach was selected by Boster (Chapter 5). With the aid of a computer, well records were analyzed for several hundred wells that have been monitored for the duration of the project. By comparing first-year and second-year chloride concentration averages, it is possible to arrive at some conclusions concerning enclave movement and dispersion.

Before discussing these results it is necessary to make some explanitory remarks. For purposes of this study, an "enclaved well" is defined as one whose chloride concentration exceeds 24 mg/l (well above the natural ground-water chloride concentrations for the area). In like manner, a "non-enclaved well" is one whose chloride concentration is less than 25 mg/l. For a two-year period, a well's "STATUS" is dependent upon its changes in chloride concentrations. A well could be an "INCREASING", "DECREASING", or "CONSTANT" well based upon the comparison of its first-year average to its second year average. A range of 10 mg/l was selected as indicating definite change; 10 mg/l represented a change of 2 ml in the titration test (Mohr method).

The theory of the mathematical model is as follows. For a random distribution of wells, enclaved and non-enclaved, predictions can be made with regard to both groupings of wells with elementary assumptions concerning ground-water movement. These assumptions include that the contaminated ground water will flow toward areas of low potential (i.e., down the water-table gradient). It has been known to hydrologists for some time that when two fluids, one highly mineralized and the other much less mineralized, contact each other they tend to form an interface rather than disperse, diffuse, or otherwise mix together. The second major assumption, then, is that the enclaves move as a "slug" rather than mixing with the surrounding fresh ground waters. The model allows for the possibility that an enclave, due to its water's higher density, may move somewhat slower than normal fresh ground water.

Consider first the non-enclaved wells. For a random distribution outside of the enclaves, it is to be expected that these wells should show a high proportion of "INCREASING" wells at the expense of a low proportion of "DECREASING" wells. This was found to be the case; for a grouping of 162 non-enclaved wells, 30 were "INCREASING", only one "DECREASING", while 131 remained

"CONSTANT". These wells are all located on farms (usually at the farm house) any may be considered randomly spaced. Several wells were drilled in the Morrow County area (designated "D" wells) to better define the enclaves for chloride mapping. Since these wells were selected for location, they could not be considered random, and therefore, were not included in the analysis.

The fact that 30 wells increased while only one decreased shows that the contamination is moving into new areas. It does not mean that the contamination is spreading in areal extent. To analyze the spreading hypothesis versus a "slug" movement theory it is necessary to consider how the enclaved wells behaved over the two-year period.

Enclaved wells were analyzed in the above-mentioned manner. For a random distribution of enclaved wells, it is to be expected that, if the enclaves are mobile, then an equal number would increase as would decrease. For the 164 enclaved wells analyzed, 46 were "INCREASING", 35 were "DECREASING", and 83 were "CONSTANT". This is a per-cent of 57 and seems well within acceptable limits. The fact that there are more increasing wells than decreasing might be due to some mixing that must occur at the enclave's edge.

The conclusions that may be drawn from these analyses is that the enclaves do indeed move, that they tend to move as a slug rather than disperse, and that there is some mixing with the fresh water surrounding the enclave.

Because of the increase in density with increased dissolved solids and in accordance with principles of flow in porous media, it may be expected that enclaves would move at a slower rate than contacting ground waters. This would imply a longer period of time required to reach effluent stream (and hence clear or "flush" the aquifer) than would be calculated based upon fresh ground-water flow velocities. In addition, Boster has pointed out that ion adsorption can be effective in retarding the migration of ions in ground water. He found that ion-exchange was a significant factor in retarding and holding anions in the soil in both the aeration and saturated zones. The implication is that due to ion-exchange phenomenon, the aquifers may never clear completely. This brings to bear the statement in the conclusion of Boster's thesis: "The length of time to pollute a significant ground-water aquifer is but a fraction of the time required to return to normalcy following such pollution." (p. 133).

CONDUCTIVITY STUDIES

It is often possible to obtain a reasonable quantitative relationship between conductivity readings and chemical titration data. In Morrow County where the contamination is mild, such a relationship was found to be very poor and indeed useless to the project. However, in the Delaware County research area where contamination is severe, conductivity analysis was found to be very helpful. The advantage to conductivity analysis is in the time saved as compared to the conventional chemical titration method.

Conductivity maps were made of the Delaware enclave in much the same manner as the isochlor maps. Samples were withdrawn from the observation wells and a sensitive conductivity instrument, an Industrial Instruments Inc. Model RB-338, was employed for the Delaware samples. Table 12 is a conductivity map prepared for Boster's thesis as Plate 5. The significance of the map lies in the configuration of the isomho lines and not in the values of the contours. This is due to the fact that conductivity is subject to considerable variation depending upon such factors as temperature and precipitation.

The similarity between this map and isochlor maps (Table 10 is an example of an isochlor map) is striking. Both isochlor and iso-conductivity maps are made from samples drawn from the same observation wells. The advantage to the iso-conductivity map is not in their ability to better describe the characteristics of the enclave (which they do not), but rather in the time saved in the laboratory. Conductivity readings can be made quickly, while titration cannot.

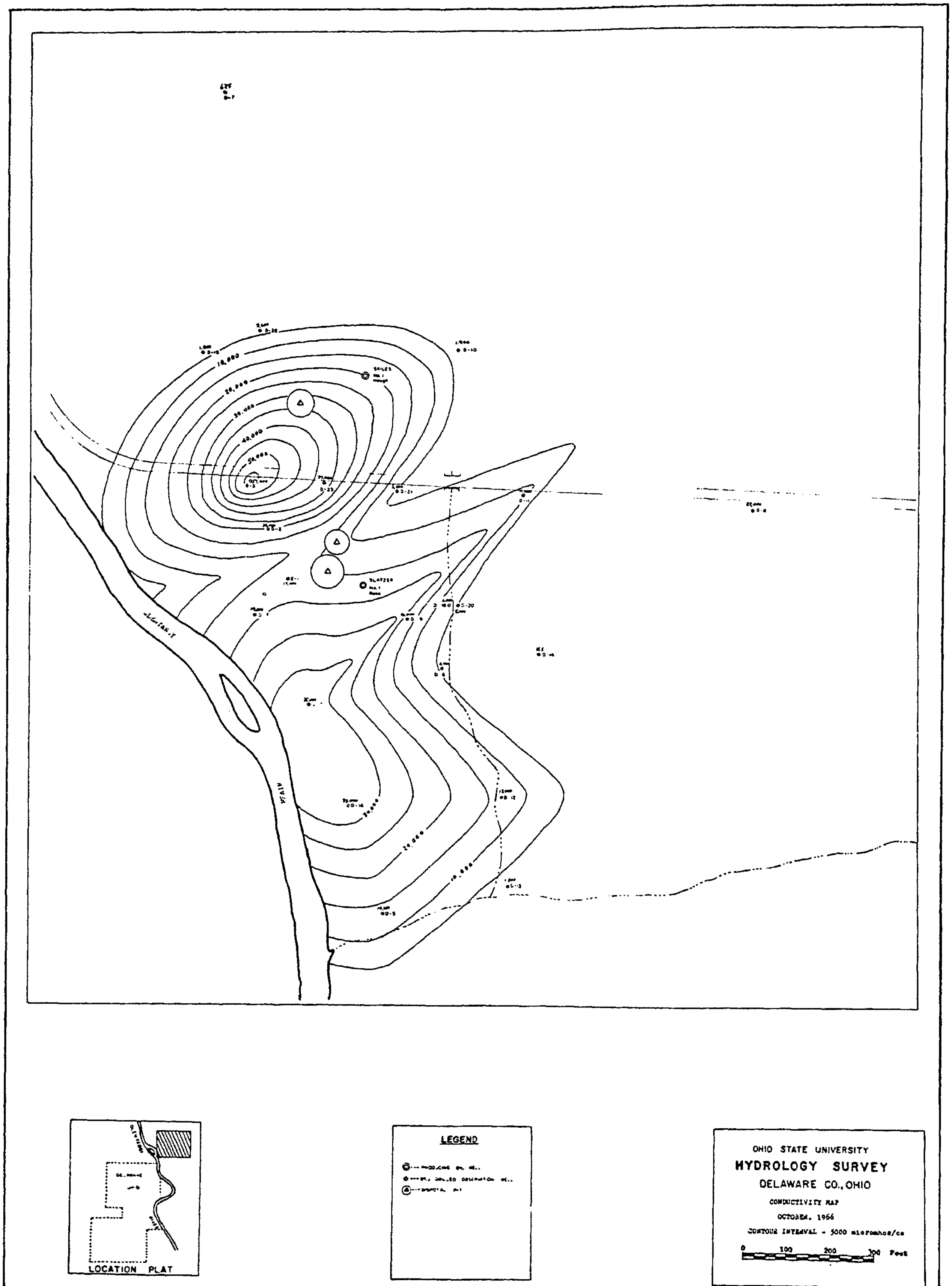

LOCATION PLAT
LEGEND
OHIO STATE UNIVERSITY
HYDROLOGY SURVEY
DELAWARE CO., OHIO
0 100 200 300 Feet

Table 12

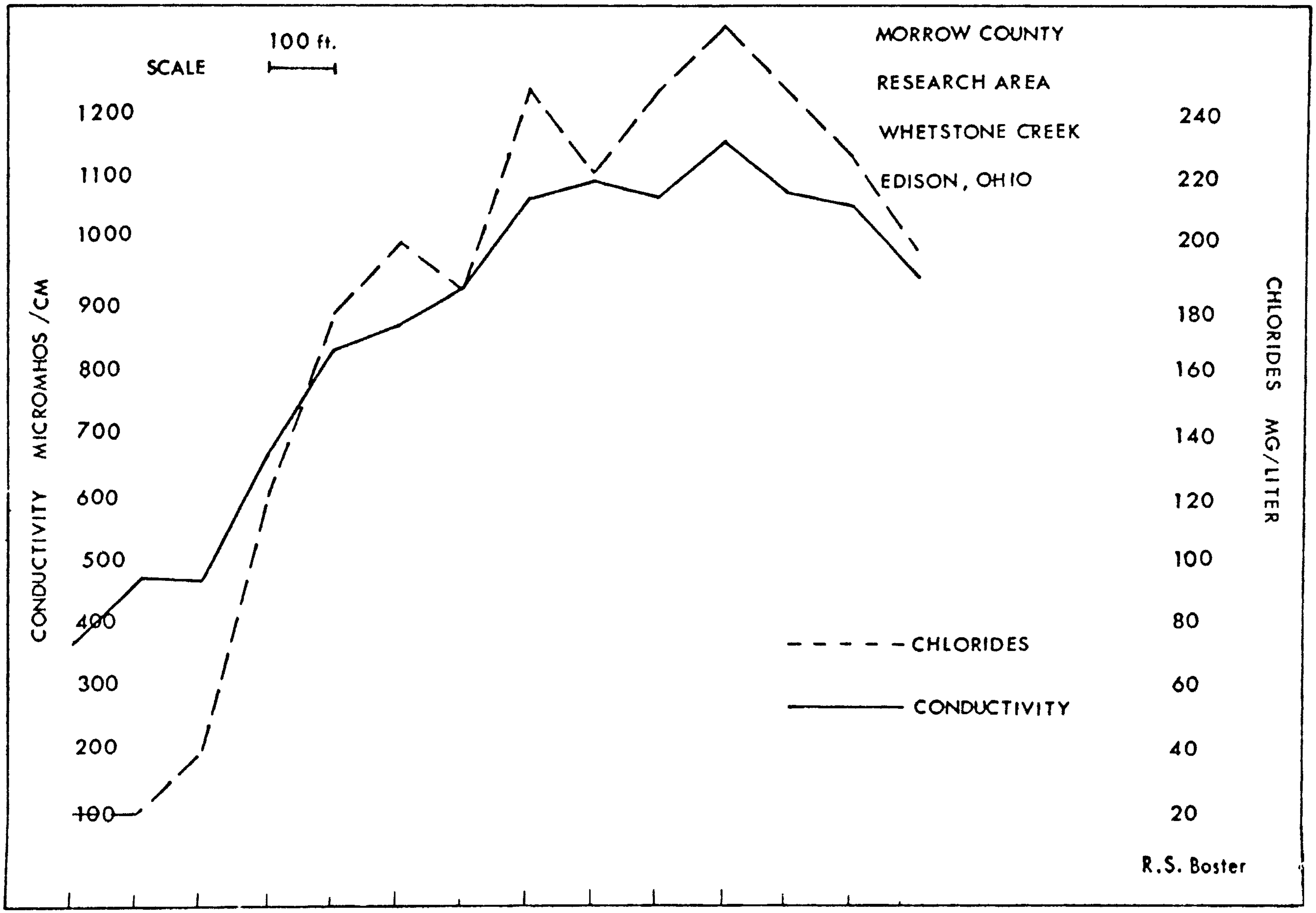
STREAM POLLUTION

The oil production occurs at varying distances from effluent streams in both study areas. Some oil wells are within several feet of either Shaw or Whetstone Creeks and the Ross No. 1 and Hough No. 1 are within 300 feet of the east bank of the Olentangy River. It is apparent from Shaw's isochlor maps and from visible vegetation along various reaches of the streams that contaminated groundwater effluent was entering the streams.

To study this aspect of the problem, conductivity and chloride surveys were made in the waterways to develop ways of detecting this type of pollution. For the most part surveys were very successful. Chapter 8 of Boster's thesis is devoted exclusively to this topic. Only the major points will be discussed in this report.

Because the location of enclaves was known from isochlor maps, and because the direction of the groundwater was determinable, it was possible to learn where effluent contaminated ground water was entering the streams. Portable conductivity meters were employed for the stream surveys and samples were collected in plastic bottles. As an example of this type of survey, Table 13 is presented (Figure 8-3, p. 125, Boster's thesis). This survey was made in the Whetstone Creek at Edison, Ohio. Disposal pits are plentiful on the floodplain immediately north of the stream at this location. (In this sense, the area is very much like the Delaware, Ohio survey area). To quote from Boster,

The results of the survey show clearly that electrolytic, high chloride



SCALE
100 ft.
MORROW COUNTY
RESEARCH AREA
WHETSTONE CREEK
EDISON, OHIO
CONDUCTIVITY MICROMHOS /CM
1200
1100
1000
900
800
700
600
500
400
300
200
100
CHLORIDES MG/LITER
240
220
200
180
160
140
120
100
80
60
40
20
CHLORIDES
CONDUCTIVITY
R.S. Boster

Table 13

> effluent is entering the stream within this reach. The correlation between chloride concentration and conductivity is especially good, but no quantitative relationship is known to exist. (p. 124)

Although not all surveys were as clear-cut as this one, the method and techniques used in this survey proved to be very effective in detecting contaminated effluent ground waters.

If the discharge of waterway is known, it is possible to calculate the weight of the effluent ground waters that enter within a given reach. This type of calculation was made adjacent to the Delaware enclave in the Olentangy river. Based upon the difference in chloride concentration (sample taken from the center of the river) from an upstream location and a downstream location, and the known river discharge (available for the U. S. G. S.), Boster made three calculations. The values obtained were 10.9, 4.4, and 7.3 tons of chloride per day for the days of June 15, July 5, and August 5, 1966 respectively (p. 122). While this seems like an enormous amount of pollution entering the river (the reach is only 500 feet long), the inflow rate was computed to be less than 0.25 cu ft per second for a ground-water concentration of 10,000 mg/l (a low value for the Delaware enclave). The equation for computing the amount of chloride effluent, worked out by Boster (p. 121) is:

$$\text{TONS OF CHLORIDE PER DAY} = \text{DELTA} \times \text{CFS} \times 2.84 \times 10^{-3}.$$

where 2.84×10^{-3} = conversion factor

DELTA = difference in mg/l chloride from the upstream to the downstream sampling station

CFS = discharge in cubic feet per second.

A point of interest noted while making river surveys was the discrepancy in laboratory and field readings for conductivity. Laboratory values were almost always higher than field results. Upon further investigation it was noted that conductivity values also varied depending upon the size and shape of the vessel in which the conductivity probe (cell) was submerged. It became clear that boundary effects have a significant effect upon conductivity readings. For this reason, the value of conductivity as a quantitative tool in hydrologic studies must be seriously questioned. Nevertheless, the value of conductivity as a qualitative tool must not be underestimated. Conductivity has proven to be a valuable investigative tool in detecting and tracing stream pollution when caused by electrolytic ground-water effluent.

No attempt was made to trace the stream pollution in the Morrow County research area downstream to the Army Corps of Engineers Flood Control Dam at Delaware (located approximately 5 miles upstream from the Delaware research area). However, it seems likely that this contamination should be detectable at the Dam. An attempt was made to trace the pollution eminating from the Delaware enclave down the Olentangy River and it was traced by conductivity readings as far downstream as Columbus, some 22 miles (Boster, 1967, p. 117). It must be pointed out that the contaminants were dilluted to insignificance as far as public health and bio-organisms are concerned.

In conclusion the project found that conductivity and chloride surveys in their waterways as described are effective techniques for detecting and tracing the pollution.

ELECTRICAL RESISTIVITY STUDY

After it became apparent that the enclave could be effectively mapped by use of isochlor maps, attention turned to other means of detection. Electrical resistivity was one of these and was the most successful. Electrical resistivity prospecting has long been used by engineers and ground-water hydrologists to determine bedrock and water-table elevations. The subject of electrical resistivity prospecting is extensive and, indeed, has filled several volumes concerned exclusively with the subject.

Briefly, the method employed by the project is based upon the fact that earth materials offer different resistances to an electric current. Actually, the resistivity of saturated materials or semisaturated materials (as in the zone of aeration) is dependent upon the fluid of the materials more so than the material itself. Because of this, it was possible to detect enclaves of ground-water contamination during this study because the contamination was highly electrolytic. Forty pages of Boster's thesis is devoted exclusively to this type of detection.

Empirical interpretation methods in common usage were employed. These were the Moore Cummulative and the Barnes layer method. In addition "simplified field analysis" was employed whereby many conclusions could be determined directly in the field. Apparent resistivity can be defined as the value calculated from the following equation:

$$RHO = 2\pi aR \qquad \text{Equation 1}$$

where RHO is the apparent resistivity
a is the separation of the electrodes (Wenner configuration)

R is the electrical resistance (ohms)

The empirical rule of Gish and Rooney is usually applied in empirical determinations. This "rule" states that the separations of the electrodes ("a") is equal to the distance of penetration of the current. Using this rule permits easy determination of the depth to certain interfaces, e.g. the water table, bedrock changes, etc.

The Moore method is a cumulative summation of the apparent resistivities at a given station and these values are plotted against the probe spacing ("a") or depth. Best-fit straight lines are drawn through the resulting points and their intersections are read off of the depth axis of the graph.

The Barnes layer method is used to evaluate the resistivity or composition of various layers of rock materials below the resistivity stations. It is based upon an analogy with parallel electrical circuitry which is not exactly the way the real situation behaves. Nevertheless, the Barnes layer method is widely used as an empirical method because it "works". The equation for the Barnes method is

$$RHO = 2\pi a\ (R_N - R_{N-1}) \qquad \text{(Equation 2)}$$

where

R is the resistance (ohms) of layer N (an integer value).

A simplified method is the following equation:

$$R_N = \bar{R}_N - \bar{R}_{N-1} \qquad \text{(Equation 3)}$$

where

$\bar{R}$ is the measured resistance. The ease of applying the above equations is apparent. By simple subtraction of readings between two probe spacing it is possible to obtain a value for the apparent resistivity or resistance (depending upon the equation employed) of the earth material in a layer whose depth is between the two probe spacings. For example, if the probe spacing is at 20 feet and a reading is taken at that spacing, and then another reading is taken at 30 feet, then the resistance of the layer of earth between the depths of 20 and 30 feet is obtained by simple subtraction of the two readings. Further, in the above example, should the apparent resistivity be desired, this difference is merely multiplied by $2\pi a$. Barnes graphs are usually presented in bar graph form.

Boster presents a new interpretative method in his thesis which is simpler to use. In essence this method is a plot of the meter reading (e.g., ohms) versus the probe spacing (depth). Best-fit straight lines are drawn as in the Moore cumulative method. When this method was compared to values from the same survey of the Moore cumulative method, it was found that the intersections of the lines was easier to pick on the Boster method than on the Moore method. In addition, and more important, there was excellent correlation between the two methods in picking water-table altitudes and bedrock interface depths. The major use of this new method was seen as a corollary use with the Moore method. By plotting both methods on the same graph paper it is possible to compare interface-depth determinations. Hence, more reliability is obtained.

<u>Method of investigation:</u> Several approaches were made to study the contamination problem utilizing electrical resistivity apparatus. The first would be resistivity mapping. Table 9 is a resistivity map made of the Delaware enclave

(Plate 9, Boster's thesis). The similarity of the enclave as depicted by resistivity and by isochlor mapping (see Table 10) is apparent. In such mapping, resistivity has a clear-cut advantage over chloride mapping. This is because of the vast amount of time and expense that can be saved by utilizing resistivity techniques. For example, it takes a system of observation wells properly developed and suitably spaced, pumping equipment, and laboratory facilities to produce an isochlor map. On the other hand, with a simple resistivity instrument (under $1000.00) a crew of two may make a map such as Table 9 in a matter of hours with no wells necessary.

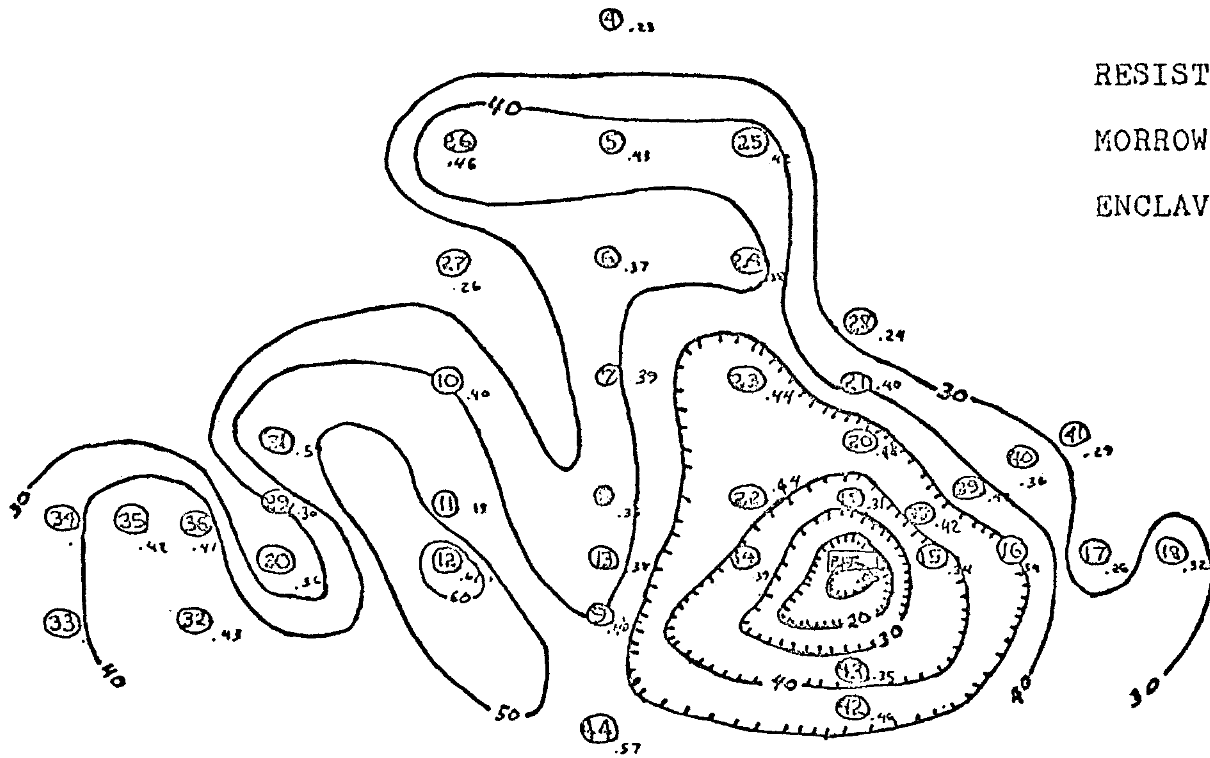
A simpler method of resistivity study is to map an area using only meter readings (ohms) rather than employing the resistivity equation (equation 1). This could be a straight reading or a subtraction reading. As an illustration of this method, Table 14 is presented. This is properly referred to as a "resistance map" since the apparent resistivities were not calculated. The reader will note the exceptionally good depression closure surrounding the lone disposal pit in the area of the map. This pit had been unused and filled over with fill for some time prior to the mapping.

It wasn't possible to make maps of the enclaves in the Morrow County survey area because access to all points was seldom possible. For this reason "traverses" were made with the equipment across a known enclave (based upon isochlor maps). At each station, a determination of the water table and the shale altitude was made. Following the traverse, the interval between the water table and the shale (the aquifer) was examined in bar-graph form to determine if it was

RESISTANCE MAP

MORROW COUNTY

ENCLAVE W-1



CONTOUR INTERVAL- 10 ohms

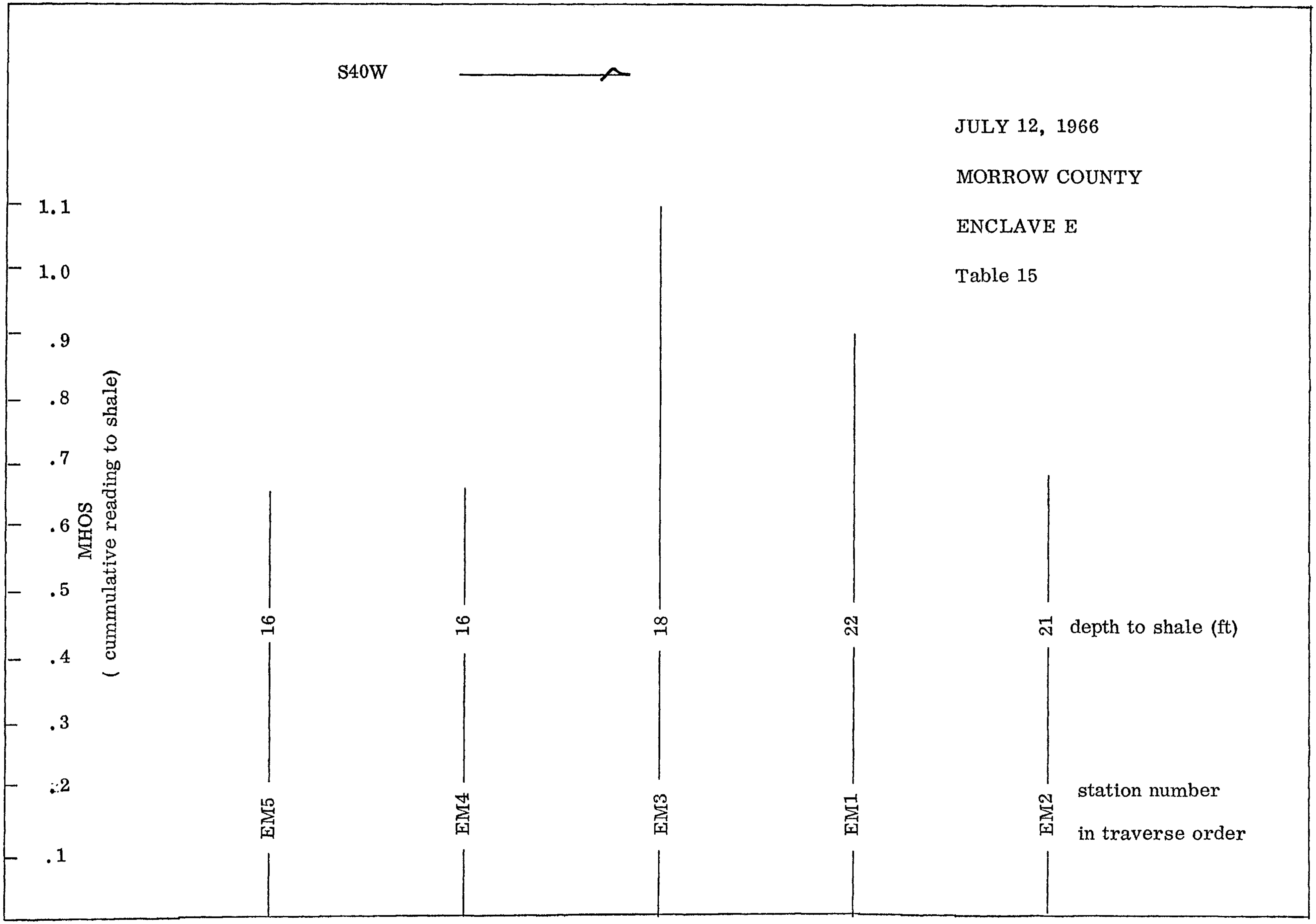
SCALE 100 feet

Table 14

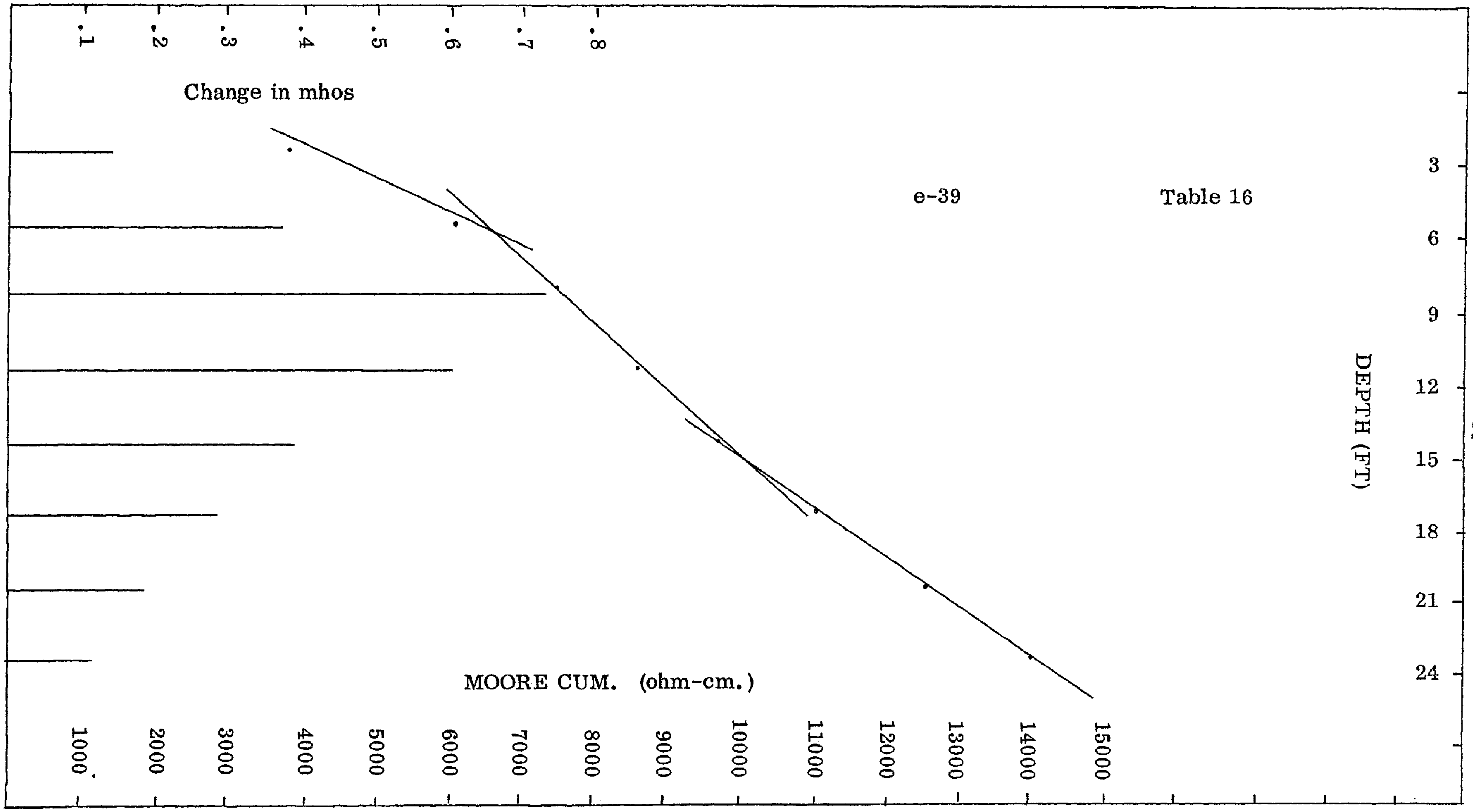
possible to detect changes in electrical properties of the water in the zone. Table 15 is such a graph of a portion of enclave E in Morrow County. The reader will notice that there is definite indication of ground-water contamination as shown by the graph.

As mentioned earlier in this report, there was evidence of chloride-concentration stratification with depth in both survey areas. Boster investigated this phenomenon with resistivity using the Barnes layer method. Table 16 is a sample graph which shows clearly that there is stratification of chlorides with depth. This is seen as a significant statement because it shows that such a conclusion can be made in the absence of wells and chloride samples.

In conclusion, the use of electrical resistivity has proven a very effective means of investigations in studies of electrolytic ground-water pollution in both study areas.



S40W
JULY 12, 1966
MORROW COUNTY
ENCLAVE E
Table 15
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
MHOS
(cummulative reading to shale)
16
16
18
22
21
depth to shale (ft)
EM5
EM4
EM3
EM1
EM2
station number
in traverse order


.1
.2
.3
.4
.5
.6
.7
.8
Change in mhos
e-39
Table 16
DEPTH (FT)
3
6
9
12
15
18
21
24
MOORE CUM. (ohm-cm.)
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000

MODEL DESIGN AND CONSTRUCTION

Directly associated with the project's field endeavors was the design and construction of a large scale ground water model that could be used to augment the field work and to develop quantitative relationships concerning a fresh-water aquifer that has experienced contamination to varying degrees. Mr. Ted Clark, who served as a research assistant for the duration of the project and who was primarily responsible for the construction of the model has written the following section of this report.

The design and construction of a large ground water testing model was the direct out growth of field research that has been going on in Morrow and Delaware Counties, Ohio over the past three years. The primary objectives of the research project has been to locate and study areas of chloride concentration in the subsurface. These areas of higher than normal (10 ppm) chloride concentration* are the result of uncontrolled and indiscriminate dumping of brine, a by-product of oil production. (Oil production has been going on in the above mentioned areas since 1961.) Unknown quantities of brine have been allowed to infiltrate into the local water source, and thus in some cases have polluted the ground water beyond the point of use.**

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* The normal amount of chloride dissolved in the ground water in the above mentioned areas is approximately 10 ppm (parts per million). For purposes of this research project, all areas having a chloride concentration of greater than 25 ppm chloride concentration are considered as areas of pollution.

** United States Public Health Service allows up to 250 ppm of chloride in water for domestic use.

The field work has been divided into two phases. The first phase was to locate and determine the areal extent of the major areas of pollution. In conjunction with this, the amount of pollution (measured in ppm of chloride) was determined for each area. Monthly isochlor maps were made of the entire area under study. The isochlor maps were made from the figures obtained by chemical analysis (a chloride titration test) on each of more than 400 monthly samples collected from domestic wells throughout the area.

This first phase of the field study, its results, figures and theories relating to the study, were worked up and published by Jimmy E. Shaw.[1]

The second phase of the original project has been under the direction of Ron Boster. There are two main objectives in the second phase of the project: (1) a continuation of the first phase, and (2) electrical resistivity and conductivity measurements made in the areas of study. The electrical resistivity and conductivity work was done to determine what, if any, relations exist between the results of this work and the results obtained by means of sample titration under the first phase.

Extensive work was done along this line and vast quantities of information was obtained.

The results of the second phase of the project have now been compiled. These findings, along with theories and generalizations will be published in the

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1. Jimmy E. Shaw, An Investigation of Ground-Water Contamination by Oil-Field Brine Disposal in Morrow and Delaware Counties, Ohio, Thesis, 1966.

near future by Boster.

Throughout all phases of this research project it has been realized that the field conditions were in no way controllable by those conducting the research.

A few of the uncontrollable conditions which have to be taken into consideration are:

1) The geology and structure of the sub-surface.

2) The drainage net and direction of drainage.

3) The amount of precipitation.

4) The exact location and amounts of brine introduced into the local water table.

5) The depth and location of the observation wells.

Because of these uncontrollable conditions, several limitations were thus imposed on some aspects of the field work. In some cases the conditions limited the accuracy of the figures obtained in the field, and thus made some interpretation necessary.

It was in part due to the uncontrollable field conditions that the proposal to build a model was conceived in which all of the above conditions could be controlled.

A model would allow checks to be made against field data, thus providing a system by which the accuracy of field data and theories could be checked.

A model would also provide a means by which new theories, not derived from field work, could be studied.

And as a final proposal, a large ground water model could be used to demonstrate the field conditions.

With these basic desires in mind, a large ground water laboratory model was designed and built. Much work went into the design of the model and several papers were written on different aspects of the overall design. With the exception of the steel frame supporting the model, most of the original principles of design were discarded for more practical features. Once actual construction was started, the observation well design and electrical system were among the major features that were modified and improved. These changes were the result of experimental work with the original designs.

The final plans led to the construction of a model as outlined in Figure 1.

The model, excluding the outside dimensions of the steel frame measures eight feet long, four feet wide and four feet deep. Within its plexiglas shell are housed two end tanks, two water inlets, two telescope drains, 18 multi-purpose wells, a conductivity monitoring system, six banks of piezometric tubes, and 120 cubic feet of unconsolidated sand weighing approximately 10,000 pounds. *

The model is so designed that water flow through the model can be in either direction. This made it possible to create a gradient which can be inclined in either direction, with a theoretical slope from 0° up to as high as 15°. **

Dye trace tubes were installed in all four corners, thus making it possible

* The entire model, under operating conditions, weighs approximately 16,000 to 18,000 pounds.

** A 15° slope is a 33.3 per cent gradient. This is a drop of 1 inch in every 3.88 inches.

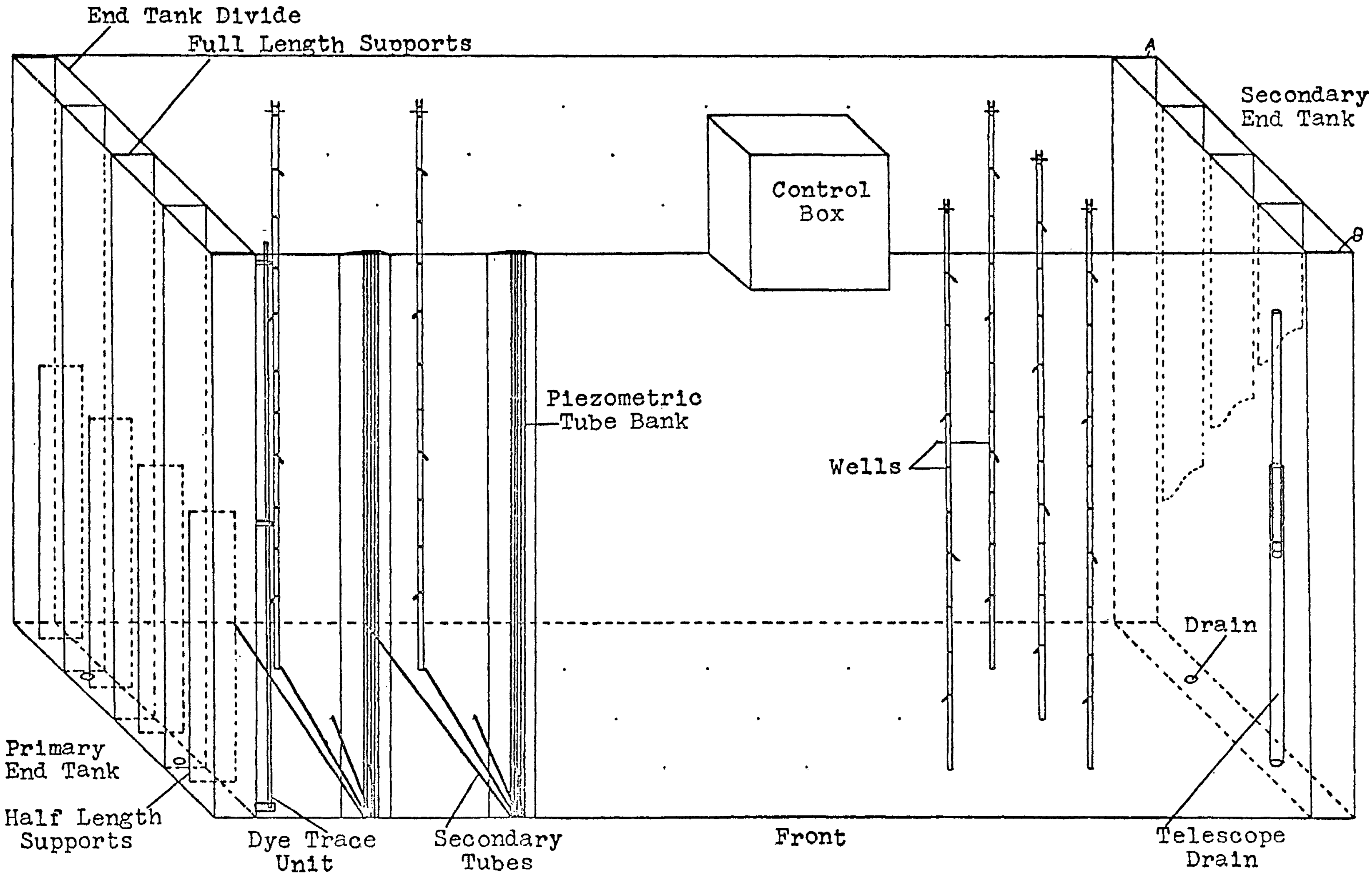

Figure 1. Basic Units of the Model (excluding the steel frame)

to observe flow lines, by means of dye injection, in either direction and on both sides of the model. Most flow net experiments will be run on the back side which is free of the piezometric tubes. Water level and pumping tests will be observed from the front side.

Initial Construction of the Model

The steel supporting structure was designed and constructed to meet the pre-determined structural requirements for such a model. The design of the steel frame was worked out by a student in the College of Engineering at The Ohio State University. The construction of the steel frame was done by a commercial welding company. The steel supporting structure is to be lined with one-half inch thick sheets of plexiglas.* Therefore the size of the model was limited to 4 x 8 feet, the size of the plexiglas sheets.

The second phase of construction of the model was the installation and sealing of the plexiglas sides and bottom.

Due to the not perfect construction of the steel frame, the bottom and two side sheets of plexiglas had to be trimmed to fit into place. The two end sheets, which fit in between the side pieces (Figure 1), had to be trimmed so that the corners would meet with little or no space between them. The same trimming was required for the two end tank divides.

Once the sides and bottom were out, trimmed and fitted in place, the

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* Plexiglas is a trade name for acrylic plastic that was used in the construction of the model.

problem of sealing them into position, and making the seal water tight, was undertaken. It was realized that with the model full of water and sand, pressures would be exerted at all points on the plexiglas. Realizing that some movement of the plexiglas at points of intersection would be encountered, a flexible type of sealer would have to be used.

A silicone sealer was found to work the best.* It proved to be quite elastic, could be removed with ease, and was not subject to any kind of biological growth. It was found necessary to abrade the surface of the plexiglas at all places which were to be sealed. This was done to insure a better bond.

Design and construction of the end tanks and water circulating system constituted the third phase of construction.

The end tanks are tanks or chambers of water located at each end of the model. It is into these end tanks that all water enters and leaves the model. From the end tank, water passes into the model through a network of screen covered holes distributed over the surface of the end tank divide, that separates the sand from the end tank. Two-hundred, 1/4 inch holes in each end tank divide

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* The silicone sealer was the third sealer used. The first was a marine sealer, but proved not to be elastic enough and thus cracked as a result of movement of the plexiglas when under pressure. The second sealer used was an aquarium sealer, which was very similar to roofing tar. Once set, it also cracked under expansion pressures. It was also subject to forms of biological growth, a process not desired in this type of model. The attempts with the aquarium sealer proved an important benefit in that it indicated where the points of maximum expansion were. These points were consequently shimed, an thus eliminated an estimated 75 per cent of the movement due to pressure expansion. This was considered an important phase in the sealing process in that the possibility of future leaks was greatly reduced. The third sealer which was used to seal the model was Dow's Silastic and G. E.'s Clear seal. Both are silicone sealers.

allow for water to move in, or out of the model with uniform distribution and a minimum of turbulence.

The inside width of the end tanks was determined to be 3 3/4 inches and the tank divide was so designed that the entire assembly could be removed if necessary to do repair work in the bottom of the end tanks. This design was worked out because, with the exception of the silicone sealer to make the model water tight, most other sealing of plexiglas was done with a sealing solution (1-B by trade name) that bonds surfaces of plexiglas in a permanent bond. If the end tank divide was sealed into position with 1-B, it would not be possible to remove it if this became necessary.

Supporting structures were cut and sealed into position for both end tanks. Five full length supports were sealed to the model, and four 1/2 length supports were sealed to the end tank divides, see Figure 1. The two outside supports, A and B in Figure 1 were sealed with 1-B to the sides of the model. The three center full-length supports, each containing thirty 1/4 inch holes for cross flow in the end tank, were sealed to the end wall of the model. The four 1/2 length supports, each with 15 holes and raised 1 inch off the bottom, were sealed to the inside face of the end tank divide. With this design, it is possible for the end tank divide to be removed. It will be held in place by the pressure of the sand forcing it up against its supports.

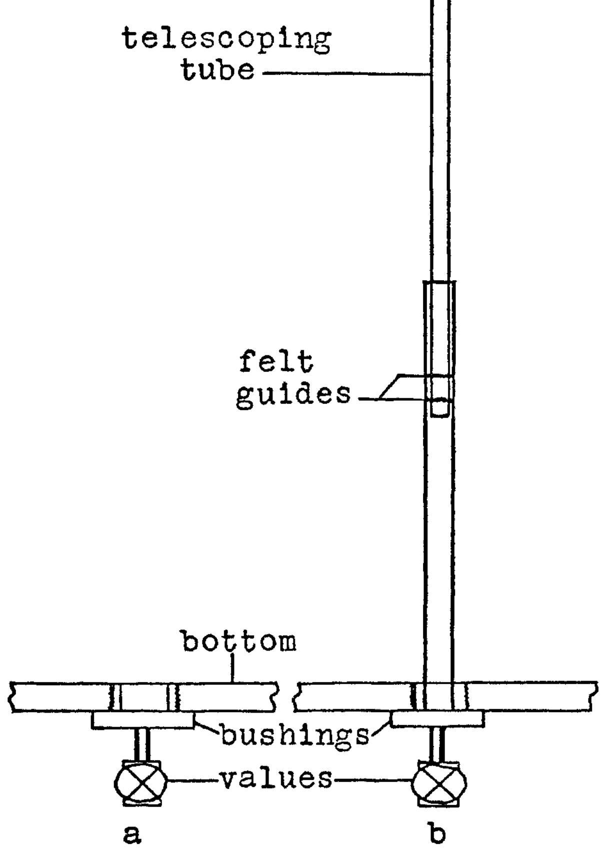
The water circulation system was also designed to allow for quick and simple replacement of parts. Four 1 3/4 inch holes were cut into the bottom sheet of plexiglas, two inside each of the end tanks at the locations indicated in

Figure 1.

Each hole was taped and a 1 3/4 x 1 1/4 bushing was sealed into each of the four holes. The bushings (one in each end tank) that are to be used as drains* were shortened so that they would fit flush with the bottom surface of the model to allow for complete drainage. See Figure 2a.

Into the other two drains was secured a telescope drain assembly. See Figure 2b. This drain design allows for any drain and overflow level desired. The inside tube moves up and down and is supported by two felt bands. All four of the drains can be removed for repair or replacement by removing the bushing. The telescope tubes are not sealed in place, thus they can be moved through the hole.

Figure 2.



Water enters the "in" tank through the regular drain and moves through the model. Excess water is drained out through the overflow drain in the "in" tank. Water moves through the model and into the "out" tank and out through the telescope drain which is set at a

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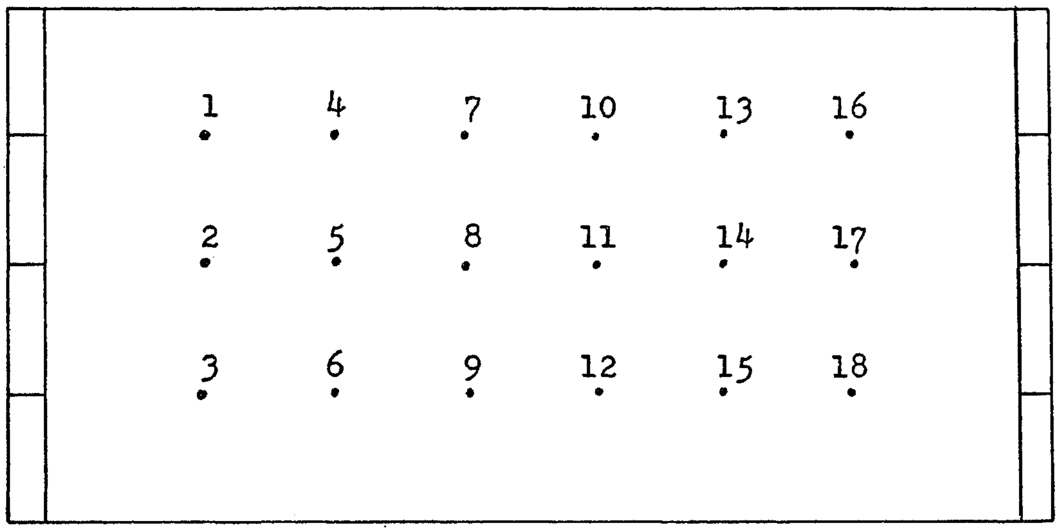
* During operation of the model, these drains will be used as the water inlets. They will be used as drains only when emptying the model completely because the telescope drains cannot drain below 26 inches.

desired level, which in turn establishes the gradient through the sand filled model.

The Observation Wells, Dye Tracing and Piezometric Systems

A uniform grid pattern of 18 observation wells was established and their locations are indicated in Figure 3.



front

Figure 3. Well Locations

The original well design was to indicate the water level in each well by means of electronic monitoring with a float device. It was soon discovered through attempts to successfully construct a well of this design that the design would have to be changed for practical reasons.* For simplicity of design, construction and operation, the idea of float level indicators was replaced with the simpler and more accurate piezometric tube system for monitoring the water

* Among the numerous problems encountered in this well design, the major one was the problem of adhesive attraction between the float device (which was an air filled tube approximately 12 to 18 inches long) and the inside wall of the well.

level in each well.

The new observation well design consists of a piece of acrylic plastic tubing (47 5/8 inches long) with an inside diameter of 1/4 in inch (5/8" O.D.). One-half an inch down from the top end of the well tube was glued a brass washer into which four 1/8 inch holes had been drilled 90° apart and just adjacent to the 1/4 inch hole in the washer. See Figure 4a.

Four pieces of 1/8 inch stainless steel tubing, measuring: 7, 19, 31, and 43 inches in length were secured to the side of the well and through the holes in the collar washer. The top ends of the tubes extend 1.2 inch above the top of the well tube. See Figure 4b. At the lower ends of each of the four water sample tubes, a piece of 60-60 mesh screen was glued to the side of the well and covering the lower end of the tube (see Figure 5). The purpose of the screen is to prevent sand from entering the tube when water samples are being withdrawn.

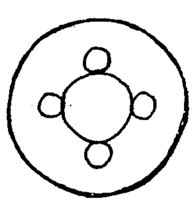


Figure 4a

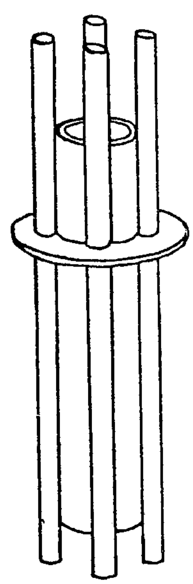


Figure 4b

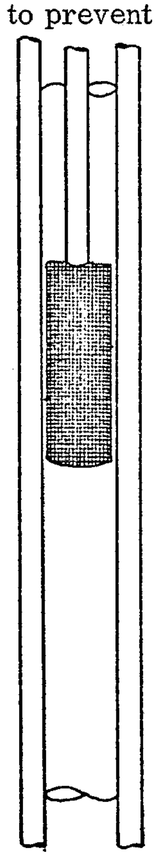


Figure 5

Along one side of the water sample tubes and running the full length of the tube, a series of 1/32 inch holes were punched into the well tube. See Figure 6. The holes average three per inch per row. The four rows of holes were punched in the plastic well tube by means of heating a piece of No. 20 copper wire attached to a soldering gun. Each well tube which contains approximately 550 holes will act as a modified well screen into which water will flow when the well is being pumped. The 1/32 inch holes are small enough to prevent sand from getting into the well tube.

The last phase of the well construction was the mounting of the conductivity probes. The conductivity probes were designed to be used with the RB3338 SOLU BRIDGE conductivity meter to measure the electrical conductance of the water moving through the model at different depths. The depths at which conductance measurements will be made are the same as those from which water samples will be extracted. Thus the conductivity probes were mounted beside the lower ends of each of the water sample tubes.

The conductivity probes were made from double conductor, rubber insulated No. 18 copper wire. About 3/4 of an inch of wire was stripped of insulation and then folded back on itself. The ends were covered with electrical tape allowing 2/5 of an inch of bare copper wire to be exposed on each lead. See Figure 7a, b, c, and d.

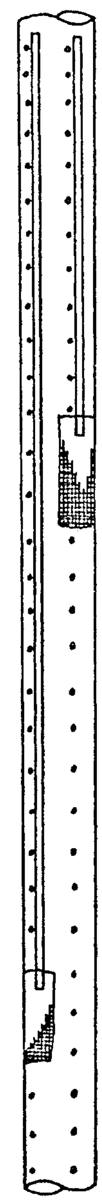
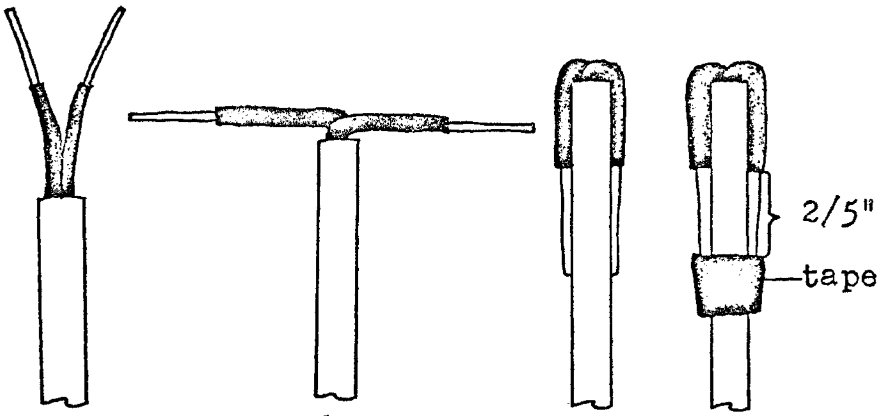


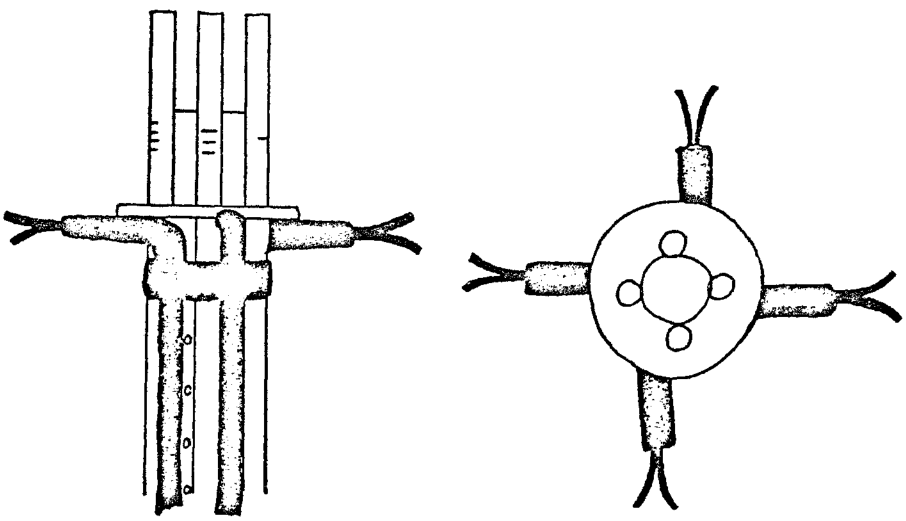
Figure 6

The completed conductivity probes were then secured to the wells with 1/4 inch strips of electrical tape as shown in Figure 8. The upper ends of the probes* extend out from under the collar washer as is shown in Figure 9. A short lead was used to tie the four common sides of each of the probes together.



a b c d

Figure 7



a b

Figure 9

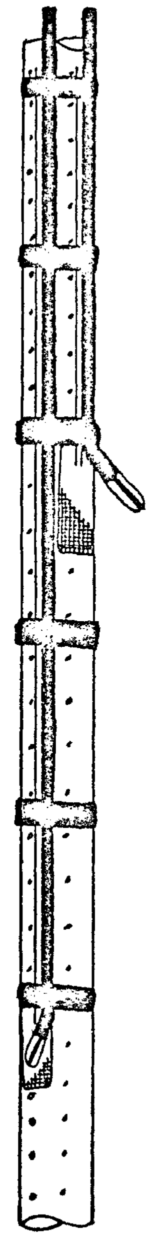


Figure 8

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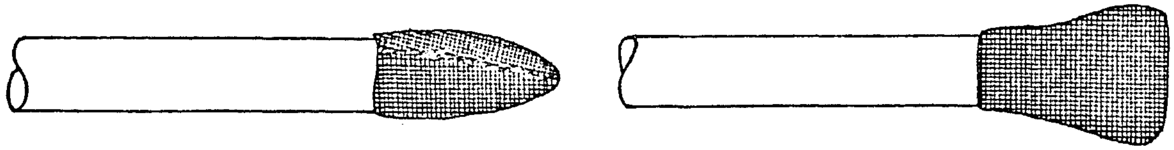
* The probe itself is bent out at about a 30° angle to prevent any interference between the probe and the well, which would affect the conductivity readings.

The piezometric tube system as used in this model will show at a glance the water level in each of the wells. Water levels, or the water table as it is more commonly called, will also be shown at six different points along each of the two sides of the model. The system thus has 30 points at which the water table is continuously indicated.

The system consists of six banks of piezometric tubes mounted on the inside of thr front of the model. Each bank contains five tubes. Three of the tubes go to three wells; the other two tubes go to the sides of the model, one to the front side, the other to the back side.

One-fourth inch (ID.) acrylic plastic tubing was also used in the construction of the piezometric tube banks. For each of the six banks, five lengths of tubing, each 46 1/2 inches long, was sealed by means of 1-B to a strip of 1.8 inch thick plexiglas measuring 2 inches wide and 47 inches long. Additional pieces of plastic tubing were cut to lengths of 1, 2, 3, and 4 feet. By means of 1 1/2 inch long pieces of flexible plastic tygon hose, these second lengths of tube were attached to the base of the bank of tubes that were mounted on the plexiglas strip. The flexible hose allows the secondary tubes to make a right angle bend so that they can run across the bottom of the model to the wells and the back side. At the end of each of the secondary tubes there is a screen tip to prevent the sand from entering the tubes. See Figure 10.



a Side view

b Top view

Figure 10

The ends of the secondary tubes that lead to wells end right at the base of each well. Each tube in the bank supports a column of water equal to the head pressure above the open screened end. When a well is pumped, a cone of depression is created around the well and the loss of head pressure is thus indicated in the corresponding tube mounted on the front side of the model.

Because the tube banks were mounted on the inside of the model they project into the sand 1/2 of an inch. This obstruction is enough to impede or distort the flow lines of water movement. See Figure 11a. The same distortion of flow lines would also be shown as distortion of dye tracing lines. To minimize this distortion, baffles were added to each side of the tube banks. A two inch wide baffle was added to the primary flow direction side.* Most of this baffle is behind major vertical steel supports and thus not seen. The other baffle is only an inch wide. It was made narrow so as not to obstruct so much of the flat surface area of the front side. See Figure 11b.

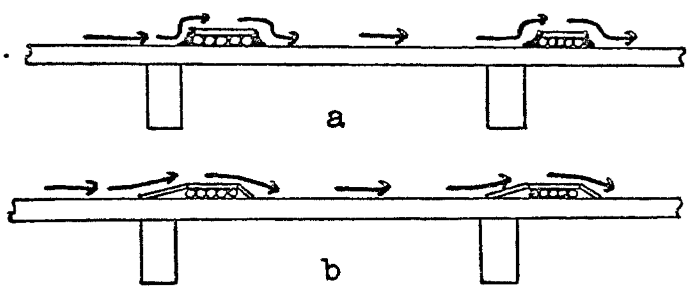


Figure 11

To continue with the versatility of the model, four dye tracing units were constructed and installed in each corner. This setup will allow dye to be introduced into the model and trace the pattern of flow lines in either direction (flow in the model can be primary from either left to right, or secondary, from right to left) and on either side (front or back).

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* Primary flow direction (from left to right, looking at the front of the model) is the direction that water will be moving for most experiments run in the model.

A dye tracing unit consists of two 4 feet by 1/8 inch steel tubes mounted beside each other, 1/4 inch apart. The outer most tube has a series of seven equispaced slits cut into it, 6 inches apart. The lowest opening is 2 1/2 inches up from the bottom of the model. The lower ends of the two steel tubes are supported and secured to the model end tank divide by means of a plexiglas block measuring 1/2 x 1 1/2 x 1 inches. Into this block was drilled three 1/8 inch holes which thus tied the two tubes together as a complete circuit. See Figure 12. The tubes were inserted into holes No. 1 and No. 2 to points B and B[1]. Hole No. 3 was sealed water right to point A. Surface S was secured to the end tank divide.

A 1/8 inch space was left between the 1 x 1 1/2 inch surface and the inside side of the model. Two guide supports for the steel tubes were also secured to the end tank divide, one in the middle and the other at the top.

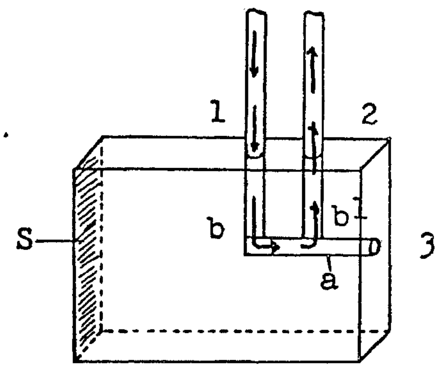

Figure 12

The Electrical System

Figure 13 is a schematic showing the wiring diagram between the top of each well and the RB3338 conductivity meter.

The well selector switch, the depth selector switch and the conductivity meter were mounted in a control box. The control box was mounted on the model frame as shown in Figure 1.

The conductivity of all 18 wells at each of the 4 depths can be read from the meter by means of selecting switch positions. Well number 18 acts as a

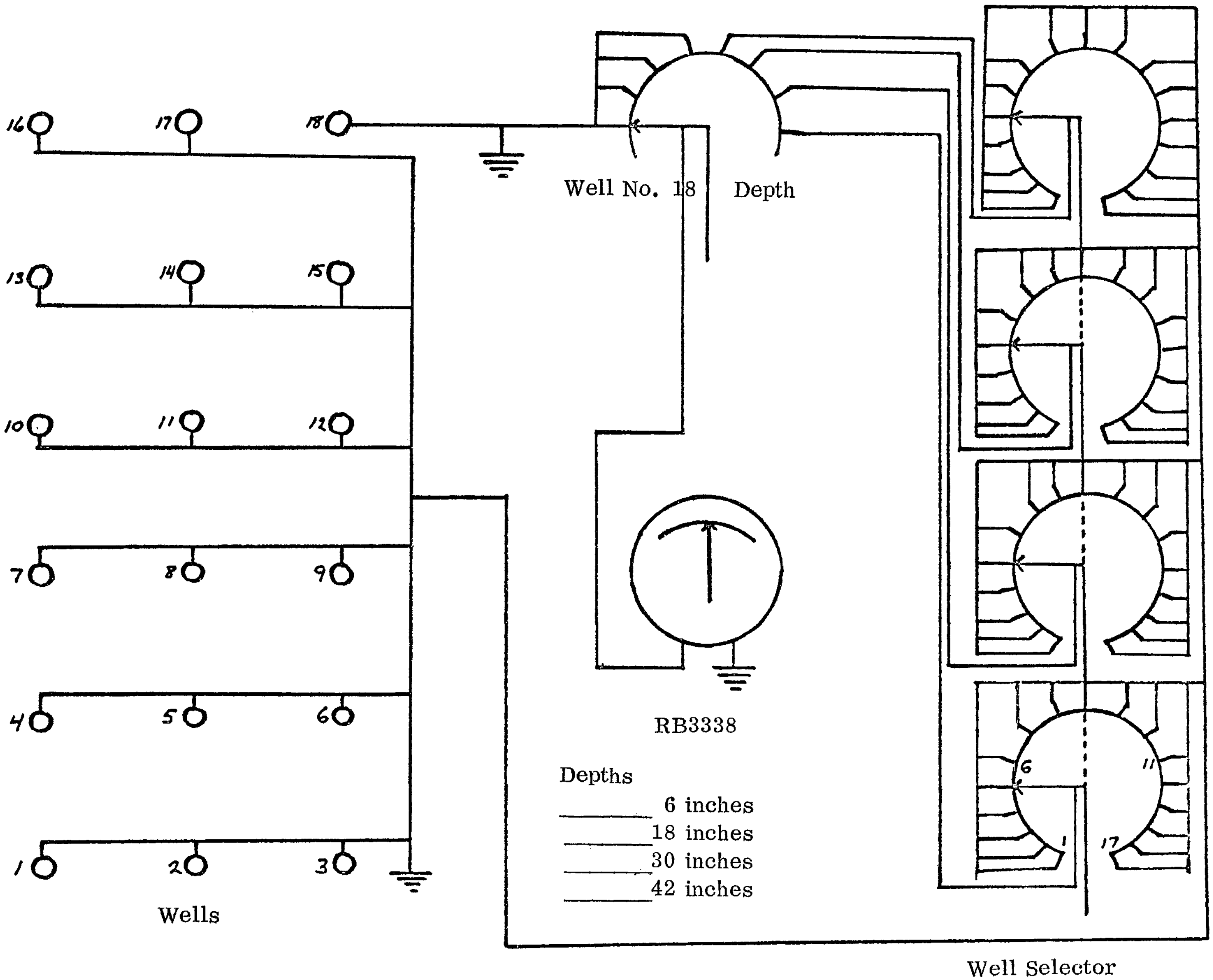
Well No. 18
Depth
RB3338
Depths
6 inches
18 inches
30 inches
42 inches
Wells
Well Selector

Figure 13

quick check monitor; i.e., four positions of only one switch will give the conductivity readings of well 18.

The RB3338 conductivity meter requires a water temperature input. A centigrade-Fahrenheit dial on the conductivity meter, set at the water temperature satisfies this requirement. Model water temperature is obtained by averaging the readings of a thermometer located in each of the two end tanks.

Setting the Wells and Filling the Model with Sand

During the entire design and construction of the model, all possible precautions were taken to insure that once the model was completed and filled with sand it would be in the best possible working order and free from faults or defects. It would require many hours and hard work to remove 10,000 pounds of sand if it became necessary to make a repair or correction. With this idea in mind, it was considered best not to secure the observation wells to the bottom of the model. Once the model was filled with sand, the sand would hold the wells securely in place. By not securing the wells to the bottom they could be removed if it ever became necessary for repair or replacement. Removal of a well would be accomplished by guiding a 1 1/2 to 2 inch thin walled length of pipe (46 inches long) down over the entire well right to the bottom of the model.* Once the pipe is in position, most of the sand around the well could be siphoned out. The well could then be pulled up and out and the remaining sand siphoned out. A new well could then

*Care must be maintained so that the end of the piezometric tube is not broken. The pipe will rest on the piezometric tube, and <u>not</u> on the bottom. A 1/2 to 3/4 inch notch could be cut into the bottom end of the pipe to fit over the tube.

be inserted into the pipe. Sand is then replaced into the pipe around the well. Once the pipe is almost full of sand, it can be removed by pulling it straight up. It is suggested that water be forced down the well while the sand is being replaced into the pipe. The water moving out through the holes in the well will aid in mixing and settling the sand, and thus prevent any pockets. It is to prevent pockets around the well and to insure well position that the pipe is filled with sand before it is removed from around the well.

The ends of the piezometric tubes were secured into position on the bottom of the model. The bases of the wells were set to one side of the screens at the ends of the piezometric tubes. See Figure 14. The tops of the wells were held in position by means of six wires stretched across the model from side to side. Three wells were held in position by each wire.

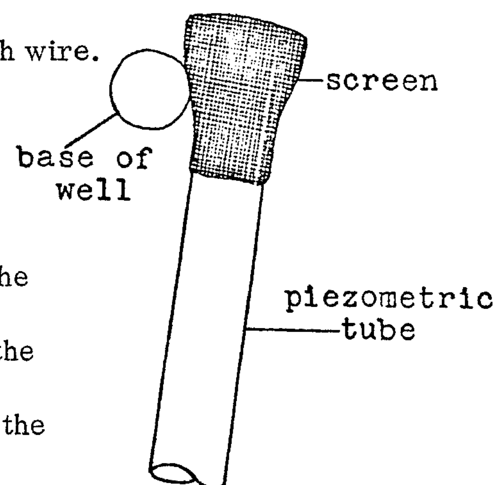

Figure 14

Once the wells were set, the model was filled about half way with water. One-hundred pound bags of flint shot sand were poured into the model, one at a time. Care was taken so that the turbulence of the falling sand would not disturb the position of the wells. Problems were encountered early in the sand filling process. Once these problems (which will be described in the next section) were corrected, the model was filled about 3/4 of the way to the top. At this point the wires that held the wells were removed. Electrical connections were made between the wells and the wires that go to the control box. The model was then filled to the top with sand.

Problems Encountered and Changes Made

This section of the report deals with the problems encountered once construction of the model was completed. Problems encountered during construction were worked out at the time of construction.

The first major problem encountered was that of sand flowing into the end tank between the edge of the end tank divide and the inside side of the model. Figure 15a is a view looking down from the top at the path taken by the sand. Point a is where the sand would start to flow through. Sand was able to flow because surfaces b and c (Figure 15 a) did not fit flush to their adjacent members. The water pressure and weight of the sand tended to spread the gaps (which were closed before the model was filled with water and sand), thus providing a path for the sand to flow into the end tank. The situation was corrected by laying a bead of silastic along the entire contact at point a (Figure 15a). See Figure 15b.

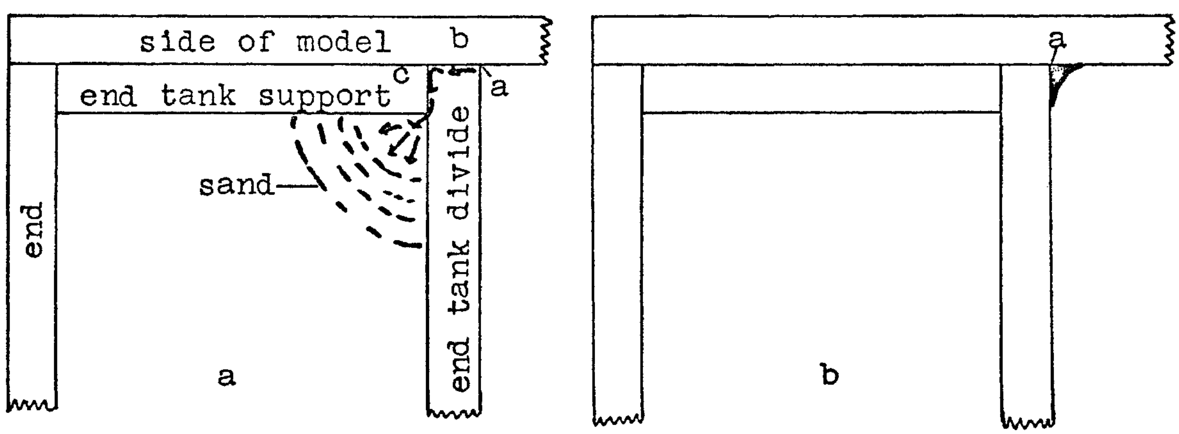

Figure 15

The second problem encountered was that of entrance loss observed between the "in" tank and the model. Figure 16 is a graph showing the slopes of the entrance losses that resulted from a series of tests conducted with five

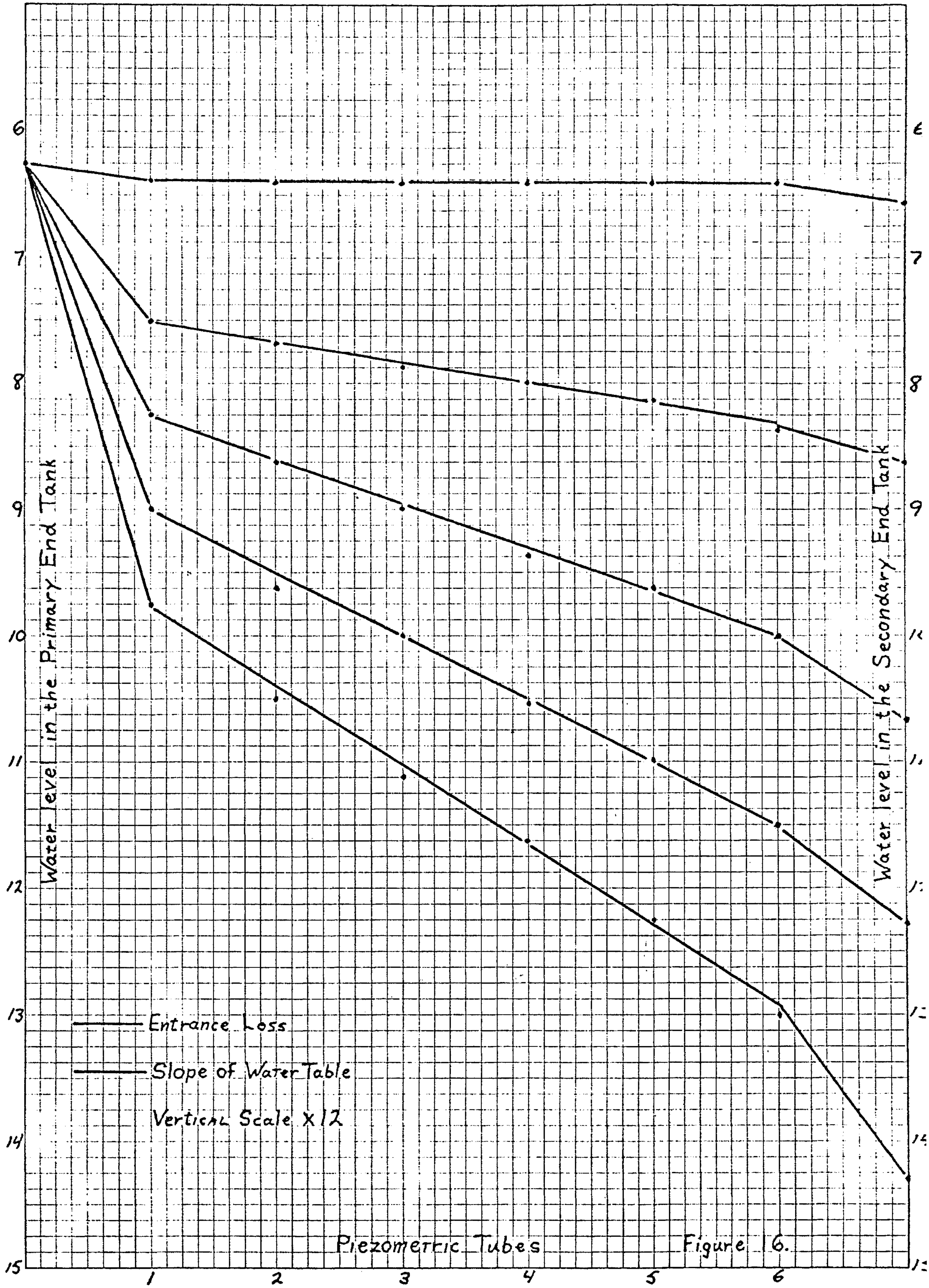
Water level in the Primary End Tank
Water level in the Secondary End Tank
Entrance Loss
Slope of Water Table
Vertical Scale X12
Piezometric Tubes
6
7
8
9
10
11
12
13
14
15
1
2
3
4
5
6

Figure 16.

different water table gradients. The causes of this problem were twofold. The major contributor to the entrance loss was the lack of holes in the upper end of the end tank divide. No holes were drilled in the upper 10 inches because it was assumed that there were enough holes in the lower 4/5 of the divide. It was not the quantity of holes that was causing the entrance loss, it was their location. With no holes at the top, water had to move in at a lower level and then try and move up through the sand to the same height as it is in the end tank. However, due to the flow pattern generated by a lower level discharge point in the other end of the model, the water does not move up, but flows away from the end tank divide towards the discharge point which is at a lower hydraulic head.

Aiding the rapid flow of water away from the end tank divide is the high permeability of the sand in the model. The high permeability is the second phase of the entrance loss problem. With high permeability, flow is fast and the water would not move through the model as rapidly which in turn would develop a steeper slope and thus create less of an entrance loss.

The entrance loss problem was reduced by the addition of a network of holes drilled in the upper end of the end tank divide. The spacing of the holes in the upper end of the end tank divide was increased to about one per square inch as opposed to one per four inches in the lower part of the divide. This addition of holes at the top end allows more water to move directly into the upper most layers of the model and thus reduces entrance loss. As with the first network of holes, the additional holes were covered with 60-60 mesh screen.

The third problem is that of the high permeability of the sand which was used to fill the model. Because of the high permeability it is very difficult to get more than 1/4 inch draw down in wells during pumping tests. With such a small draw down, a very shallow cone of depression is all that is observed.

To lower the permeability would require replacement of the coarse sand now in the model with a finer sand. However, at the time of this report, the reasons against this action far outweigh the necessity of this changeover. All original experiments for which the model was designed will be able to be run.

A less complex problem involved the operation of the dye trace units. It was soon discovered that the holes in the steel tube through which the dye is introduced into the model were too large. The large holes resulted in trace line up to 4 inches in width. The desired tracer is from one to not more than two inches in width for this model.

The problem was solved by the construction of a single, portable dye trace tube. The original dye trace units were left in place, as is. The new unit consists of a single 1/8 inch steel tube, four feet in length. The lower end was pinched shut. Ten holes were cut into the tube, equispaced 4 inches apart, with the lower hole 2 inches from the closed end of the tube. The holes in the new tube are about 1/4 the size as those in the original units.

The single tube can be considered portable because it can be inserted into the sand at any location in the model. Being of such a small diameter (1/8 inch) it can be pushed down into the sand with very little effort. The dye lines of the new unit fall within the desired limits, and thus provide a neat and easily traceable flow pattern.

The problem of sand stratification and pockets in the sand filled with water and/or air was also encountered. Most of the sand was poured into the model while the model was partially filled with water. This was done in the hopes of preventing air pockets that could result from filling the model with dry sand. Air pockets would tend to form around the wells and at other critical locations. Having the model filled with water prevented air from being entrapped, and also aided in spreading the sand around the wells. The problem encountered was that the water also sorted the sand which resulted in thin layers of the finer material being deposited after the coarser sand. These thin layers show up as cross-bedding with angles and their extent dependent upon the distribution of the sand at the time of pouring.

The problem was solved by filling the rest of the model with dry sand. The sand, once poured into the model was then spread around by hand to insure even and uniform distribution. The problem of the cross-bedded and sorted sand was somewhat eliminated by means of reworking the sand with a water hose and water under pressure inserted into and moved through the stratified sand.

Testing, Experiments and Potential Uses of the Model

The initial test was developing a water table gradient in the model. This was accomplished by means of water inflow at one end of the model and a discharge at the other end. This test indicated the problems of high permeability and the entrance loss at the "in" end tank. Well pumping tests, and the resulting shallow cone of depression, confirmed the high permeability situation.

The high permeability of the model will have very little effect on the experiments to be conducted. The draw down in and around the wells, which develops during pumping tests, will not be as greatly exaggerated as it would be if the permeability was lower. In all reality, the scale of draw down will be closer to that observed in the field.

Testing of the dye tracing units resulted in the construction of the better and more practical single tube units. The resulting dye trace lines from the new units were what was desired.

Initial testing of the conductivity and water sampling systems was good. Small quantities of water are removed from each of the four water sampling tubes on each well. These samples are then titrated and the data is correlated with the conductivity figures for the same well and depth.

Initial experiments show that chloride solutions introduced into the model, move through the model as units. Chloride solution units are introduced into the model by means of a surface pit, or by injection into the sand at predetermined depth. Injection of the solution is by means of an open end tube inserted into the sand. The size of the chloride unit depends on the volume of solution used and the duration of the injection period. Two basic patterns are used when tracing chloride units in the model. The first pattern is to introduce the solution as a single unit of short duration. The movement of this unit is then followed. The second pattern is to introduce a continuous supply of solution. The boundaries are then observed and determined once equilibrium is reached.

Once chloride solution units have been introduced, their movement is traced by means of conductivity measurements. These units have been observed to move as units, with very little diffusion and dispersion. No residual trace of chloride remained or lagged behind once the unit moved through a given area.

Wide variations of the above stated experiments can be conducted. Changes in water table gradient, various concentrations of chloride solutions and fluctuations in the duration of injection periods are but a few suggestions that will give a wide range of results.

Experiments in flow line movement that result from pumping different wells at different rates, aided by the observation of dye trace lines will add another series of experiments.

Recharge systems, influent and effluent stream studies and gradient versus velocity problems are additional experiments that can easily be incorporated into the model. It is the opinion of those involved in the design and construction of the model that a wide range of theoretical as well as actual field conditions can be studied within the confines of this model.

SUMMARY AND CONCLUSIONS

Ground-water contamination by brine introduced at the surface in Morrow County appears to be quite widespread, but only four areas have been located where contamination levels have exceeded the U. S. Public Health drinking water standards. This contamination appears to be clearing up.

The areal extent of the contamination in Morrow County is approximately 13 square miles. Evidence indicates that spreading has been minimal. Further, the contaminated ground water tends to move as a slug rather than mixing with contacting fresh waters.

The bulk of ground-water contamination has occurred in the vicinity of oil production, but some is occurring down the water-table gradient to the south. The vast majority of the contamination in Morrow County is attributed to petroleum exploration and production. The major contributors to contamination have been salt-water "evaporation" pits and indiscriminate dumping of salt water by contract truckers.

The ground water near two disposal pits at Delaware, Ohio, became extremely contaminated. Chloride concentrations in the ground water at times (August, 1965) exceeded the concentration of the brine being produced by the oil wells. Contamination has been confined to approximately 20 acres along the Olentangy River, and a serious problem, affecting many people, has been averted only because of the geologic and hydrologic parameters of the area. Continued study in the Delaware County area has led to the conclusion that the enclave there is far from dissipated. Somewhere between 1969 and 1972 seems to be the best approximation at this time of a clearing date for the Delaware enclave.

Over the Morrow County area, shallow wells show greater chloride concentrations than the deeper wells. Also, dug wells appear to catch more contamination than drilled wells. At Delaware, the shallow levels of the reservoir carried the bulk of the contamination at first, but with time and continued salt-water introduction through the pits, inversion occurred and the deeper levels became more contaminated. This salt water inversion is probably also occurring over Morrow County but lack of control has not allowed its definition.

The fresh water contamination will not ameliorate rapidly. Areas of contamination near effluent streams will probably take several years to flush, provided contamination at the surface is discontinued; areas two to three miles from the streams may take several tens of years to clear up.

The importance of ion-exchange phenomena can not be underestimated and its role in ground-water pollution may be extensive. Resistivity studies have reinforced this contention by indicating soil contamination in the zone of aeration. Ion-exchange phenomena may greatly extend the time period required for natural clearing of an enclave.

The addition of resistivity and conductivity techniques to supplement chloride analysis was successful in this study. However, special conditions are necessary for successful implementation of these techniques and, in fact, new techniques were often needed to obtain meaningful results. In the Delaware enclave, an area of intense ground-water contamination, conductivity analysis was found effective in depicting the characteristics of the enclave. In areas of less intense contamination, e.g., Morrow County enclaves, conductivity was ineffective. Resistivity was found to be very effective in the detection of contaminated ground waters in both research areas. The practical application of resistivity leads to the conclusion that it can be a valuable investigative and diagnostic tool in ground-water pollution studies. Resistivity has a decided advantage over chloride and conductivity analysis in that fewer observation wells are required, thus much time and expense can be saved.

Contamination has occurred in the streams adjacent to enclaves. This is in accord with normal and well-known hydrologic principles concerned with effluent streams. The stream pollution is easily detectable by field and laboratory techniques described in the text utilizing conductivity instrumentation and chloride analysis data. The most serious area of stream pollution appears to be adjacent to the Delaware enclave. It was calculated that several tons of chloride enters the Olentangy River in one day. The chloride is diluted appreciably downstream, but is detectable as far south as Columbus. No public health problem has or is expected to occur from effluent, polluted ground waters resulting from oil-recovery operations in either study area.

Ohio has taken a late but significant step toward the elimination of ground-water pollution from oil field operations. Unfortunately, laws had to be enacted because of a regretable situation in Morrow County, Ohio and the lack of effective legal control. It is highly unlikely a similar situation will ever again occur in the state. Preferably states should enact legislation with proper enforcement provisions to guard against the impairment of the quality of ground-water resources. Legislation "before the act" is vital. The use of unlined evaporation pits in humid areas where fresh ground water may be contaminated by brines especially should be prohibited. Fresh ground water is a natural resource that should be jealously guarded. Its importance is constantly growing, and the public cannot afford to allow it to be spoiled by uncontrolled disposal of waste products.

The ground water quality in Morrow County has been altered, but there is little need for alarm as very few people have or will be affected. Some domestic wells had to be abandoned, however, the chloride concentration in the vast majority of wells in Morrow County are well below the federal standards for drinking water. Nevertheless, the importance of potable water to a rural dweller must be recognized and respected by those who affect or who are capable of affecting ground water quality. It is an expensive and frustrating endeavor for a person to be forced to drill a new and deeper water well only because of the actions of others.